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Energy and Precious Fuels Requirements of Fuel Alcohol Production

Volume II—Appendices A and B: Ethanol from Grain

Herbert Weinblatt
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December 1982

Prepared for
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Chevy Chase, Maryland 20815

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Battelle Columbus Laboratories
Columbus, Ohio 43201

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Center for Agricultural and Rural Development
Iowa State University
Ames, Iowa 50011

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FOREWORD

The study presented in this report was funded by the U.S. Department of Energy (DOE) and performed under Contract No. DE-AC01-80CS50005 with DOE and Contract No. DEN3-292 with the National Aeronautics and Space Administration (NASA) under Interagency Agreement DE-AC01-81CS50006. The work was performed by Jack Faucett Associates, with subcontractual assistance from Battelle-Columbus Laboratories and from the Center for Agricultural and Rural Development of Iowa State University. DOE responsibilities were carried out by E. Eugene Ecklund of DOE's Office of Vehicle and Engine R&D, and Dr. Daniel P. Maxfield of the same office assisted him. NASA responsibilities were carried out by George M. Prok of the Aerothermodynamic and Fuels Division at NASA-Lewis Research Center, Cleveland, Ohio.

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This report is the product of a team of persons from Jack Faucett Associates (JFA), Battelle-Columbus Laboratories (BCL), and the Center for Agricultural and Rural Development (CARD) of Iowa State University (ISU). Dr. Herbert Weinblatt and Michael F. Lawrence of JFA had overall responsibility for performing the study. Dr. Weinblatt had primary responsibility for final editing and for preparing Volume I and Appendices A and G of the report. Rena K. Margulis of JFA was responsible for Appendix E. Geoffrey Back of JFA was responsible for Appendix D and contributed to Appendix G.

David M. Jenkins had overall responsibility for BCL's contributions to the report. T.S. Reddy of BCL drafted Appendices B, F and H. Karen St. John of BCL drafted Appendix C, and Dr. Thomas McClure of BCL contributed to Appendix A.

Dr. Anthony J. Turhollow, Jr., of CARD performed all runs of the ISU Model reported in Appendices A and E and contributed to the drafting of Appendix A.

Thomas J. Timbario of the Transportation/Fuel Systems Department of Mueller Associates, Inc., Baltimore, Md., along with members of his staff, provided consultation and critiqued all draft reports.

The manuscript was typed by Pamela C. Brockington with assistance from other members of the JFA secretarial staff.

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VOLUME II

ABBREVIATIONS

B	billion
Btu	British thermal unit
bbl	barrel
bu	bushel
C	Centigrade
cu ft	cubic foot
cwt	hundred weight (100 lb)
d	distance
DDG	distillers' dark grains
DTE	dry ton equivalent
F	Fahrenheit
gal	gallon
ha	hectare
HHV	higher heating value
hp	high pressure
hr	hour
K	Potassium
kw	kilowatt
kwhr	kilowatthour
lb	pound
lp	low pressure
LPG	liquefied petroleum gas
M	thousand
MLRA	major land resource area
MM	million
N	Nitrogen
P	Phosphorus
psia	pounds per square inch absolute
psig	pounds per square inch gauge
T	trillion
wt	weight
yr	year

BTU CONVERSION FACTORS

Fuel	Units	HHV
Coal	Btu/ton	22,500,000[a]
Distillate	Btu/gal	140,000
Electricity Consumption	Btu/kwhr	3,413
Ethanol	Btu/gal	84,200
LPG	Btu/gal	95,000
Lubricating Oil	Btu/gal	145,000
Methanol	Btu/gal	64,350
Motor Gasoline	Btu/gal	125,000
Natural Gas	Btu/cu ft	1,020
Residual Fuel Oil	Btu/gal	150,000

ELECTRICITY CONVERSION FACTOR

Fuel	Btu's consumed/Btu electricity produced
Coal	3.05

[a] *When no specific coal characteristics were known, the energy content of a "standard ton" of coal (22,500,000 Btu) was used. Other values were used when more appropriate and are indicated in footnotes.*

SI CONVERSION FACTORS

1 acre	=	4046.8564 square meters
1 bbl	=	158.98284 liters
1 Btu	=	1054.35 joules
1 cu ft	=	0.028316847 cubic meters
1 gal	=	3.7854118 liters
1 lb	=	453.592 grams
1 mile	=	1609.344 meters
1 psi	=	0.0680460 atmospheres
1 ton	=	907184.74 grams
273.15 + 5/9(F-32)	=	degrees Kelvin
273.15 + C	=	degrees Kelvin

OTHER CONVERSION FACTORS

1 acre	=	0.40468564 ha
1 bbl	=	42 gal
1 Btu	=	252 calories
1 bu barley	=	48 lb
1 bu corn	=	56 lb
1 bu grain sorghum	=	56 lb
1 bu oats	=	32 lb
1 bu soybeans	=	60 lb
1 bu wheat	=	60 lb
1 psi	=	6895 pascals
1 square mile	=	640 acres
1 ton	=	2000 lb

APPENDIX A

AGRICULTURAL CROP RESOURCES

Carbohydrates for ethanol production via saccharification and fermentation can be obtained from any crop containing starch or sugar. If a significant volume of ethanol is to be obtained for fuel, however, it must be obtained from sources which are capable of supplying large volumes of carbohydrates at relatively low cost. The agricultural resources with the greatest apparent potential are the grains.

In this appendix, two sets of estimates of energy requirements for grain production are developed. The first is a set of estimates for average energy requirements for current production of five grains (corn, grain sorghum, winter wheat, barley and oats). The second is an estimate of the increase in energy consumption which will occur if production of two of these grains (corn and grain sorghum) is increased so that they can be used as ethanol feedstocks while production of soybeans is decreased (as a result of the availability of high-protein feed by-products of the ethanol process). The estimates of energy requirements for ethanol production presented in the body of this report are based on this latter estimate (which is developed in Section A.2.1, below). A discussion of the sensitivity of this estimate to the assumptions used in its development and to potential changes in the agricultural production system is provided in Section A.2.2, and a discussion of the energy credits for the by-products of ethanol production is contained in Section A.3. The estimates of average energy requirements for current grain production were not used in this study but are presented in Section A.1 for comparative purposes. Brief discussions are also included (in Section A.4) of the overall potential for converting additional land to crop use and for increasing grain production for conversion to ethanol.

A.1 Energy Currently Used in Grain Production

Various authors have estimated the quantity of energy consumed in grain production. Each has approached the question in a slightly different way, reflecting their own views and chosen assumptions. In addition to individual attitudes, the different approaches reflect the various methods of producing grain, in which planting rates, fertilization rates, tillage practices, drying methods, and need for irrigation may vary according to

climate, soil, latitude, etc. These variations naturally affect the amount of energy consumed in producing the crop.

The baseline data for the estimates of energy currently used in producing grain crops presented in this section were taken from Energy and U.S. Agriculture: 1974 Data Base, Volumes 1 and 2 (USDA, September 1976 and April 1977).[1] In this study, an agricultural energy accounting model was developed to accommodate energy data in a systematized framework. The model contains five major dimensions: energy, geography, commodity, time, and function. The energy sector consists of consumption, by crop, of gasoline, diesel fuel, fuel oil, LP gas, natural gas, electricity, and the energy invested in producing and transporting fertilizers and pesticides. The fifty states represent the geographic dimension, with over 70 crop and livestock commodities being detailed in the study. The functional breakdown includes all energy-using operations which occur on the farm for crop or livestock production purposes as well as a share of other energy consumed by farms (e.g., "farm auto" and "farm pickup").

A subsequent USDA study by Torgerson and Cooper (1980) (Energy and U.S. Agriculture: 1974 and 1978) revised the 1974 estimates and also updated them to 1978 levels to reflect changes in fuel usage due to changing technology, energy conservation measures, real petroleum prices, etc. The resulting estimates of national energy consumption in 1978 for all crops are presented in Exhibit A-1. It can be seen that the largest single component of energy use in crop production is for fertilizers, which account for approximately 33 percent of total Btu usage. Nationally, the second largest energy consumer is irrigation, which accounts for approximately 20 percent of total usage. However, usage for irrigation varies substantially between states -- such usage is negligible in some states (e.g., Wisconsin) while it is the dominant energy consumer in other states (e.g., Arizona and New Mexico).

For consistency with data presented throughout this report, the estimates of total energy requirements for each operation shown in Exhibit A-1 were derived from data on fuel requirements shown in the table and the Btu conversion factors used throughout this study (see page xv), and so differ somewhat from those provided in the source. In particular, the energy required for electricity has been estimated as 10,400 Btu coal per kwhr of electricity consumed.

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[1] *Parenthetical references to authors (or publishers) and dates identify bibliographic references. Full citations are contained in the bibliography at the end of this volume.*

EXHIBIT A-1: TOTAL ENERGY CONSUMPTION FOR AGRICULTURAL CROPS (1978)

	Petroleum Products								
	Motor Gasoline (M gal)	Distillate (M gal)	Residual Fuel (M gal)	LP Gas (M gal)	Natural Gas (MM cu ft)	Electricity (M kwhr)	Invested Energy (1) (B Btu)	Total Energy of Identified Petroleum Products (2) (B Btu)	Total Energy (3) (B Btu)
Preplant	45,949	1,212,328		17,214				177,105	177,105
Plant	31,178	315,600		2,076				48,278	48,278
Cultivate	20,310	338,682		5,406				50,468	50,468
Harvest	523,994	582,510		88,593				155,467	155,467
Farm Pickup	1,018,323	1,057		22,234				129,551	129,551
Fertilizer Appl.	24,251	70,084		2,567				13,087	13,087
Pesticide Appl.	25,271	92,764		9,535				17,052	17,052
Farm Truck	535,485	5,747						67,740	67,740
Farm Auto	486,159							60,770	60,770
Grain Handling (Vehs.)	15,253							1,907	1,907
Grain Handling (Mach.)						34			354
Crop Drying			62,102	629,396	700	565		69,108	75,698
Irrigation	73,622	136,894		242,512	134,222	19,453		51,407	390,624
Frost Protection	38,866	27,634	218,548	1,458		200		41,648	43,728
Fertilizer							652,532		652,532
Pesticides							68,130		68,130
Electricity						1,696			17,638
Miscellaneous	72,633	37,162						14,282	14,282
TOTAL ALL CROPS	2,911,293	2,820,464	280,651	1,020,990	134,923	21,948	720,662	897,870	1,984,411

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Source: Derived from Torgerson and Cooper (1980).

Energy identified in Exhibit A-1 as being derived from petroleum products represents about 45 percent of the total. In addition, about 7 percent of the energy invested in fertilizer and pesticides is from petroleum products. (The USDA reports do not provide an explicit breakdown of the sources of energy used for producing and transporting fertilizer and pesticides, though an approximate breakdown will be developed later in this appendix.) Overall, petroleum products provide about 49 percent of total agricultural energy requirements. Natural gas provides about another 33 percent of these energy requirements, primarily in the form of energy "invested" in fertilizer.

A comparison of national energy use for crop production in 1974 and 1978 is shown in Exhibit A-2. During this period, there was a substantial increase in the production of most major crops, though not in acreage planted. Energy consumption increased 6.2 percent overall, and energy consumption per acre increased 4.4 percent. Most of the increase occurred in the use of diesel fuel and invested energy. The increase in diesel fuel consumption is partly due to a switch from gasoline to diesel fuel, but overall the increase in consumption of petroleum products accounts for more than half the increase in energy consumption. The increase in invested energy primarily results from increased fertilizer usage.

The 1978 estimates and the revised 1974 data base did not provide the detailed energy consumption for each crop which was included in the original 1974 estimates. Therefore, to estimate usage for specific grain crops grown in each state, it was necessary to disaggregate the 1978 data, which was reported only for all crops in the state. This disaggregation was accomplished in the following manner:

1. The first step was to identify and select the states that were representative of (a) low energy, (b) medium energy, and (c) high energy consumption per bushel of grain produced for the five selected grains: corn, grain sorghum, winter wheat, barley, and oats. Three states were selected for each crop based upon the data presented in the 1974 detailed study. The selection criteria consisted of a combination of the number of acres planted to the specified crop, the energy consumed per acre, and the crop yield per acre.

2. Following the selection of the states, the next step was to determine the amount of energy consumed by type (gasoline, diesel fuel, LP gas, etc.)

EXHIBIT A-2: COMPARISON OF ENERGY USED IN U.S. CROP PRODUCTION, 1974 AND 1978

	Total Energy Used				Energy Use Per Acre Planted (1)			
Energy Type	Units	1974	1978	% Increase 1974-78	Units	1974	1978	% Increase 1974-78
Gasoline	MM gal	3,042	2,911	-4.3	gal/A	9.23	8.69	-5.9
Diesel Fuel	MM gal	2,284	2,820	23.5	gal/A	6.93	8.42	21.5
Fuel Oil	MM gal	283	281	-0.7	gal/A	0.86	0.84	-2.3
LP Gas	MM gal	989	1,021	3.2	gal/A	3.00	3.05	1.7
Natural Gas	MM cu ft	132,809	134,922	1.6	cu ft/A	403.1	402.8	-0.1
Electricity	MM kwhr	21,737	21,948	1.0	kwhr/A	66.0	65.5	-0.8
Invested Energy	T Btu	671	721	7.5	M Btu/A	2,036.	2,152.	5.7
Total (2)	T Btu	1,869	1,978	6.2	M Btu/A	5,654.	5,906.	4.4

(1) Planted area of principal crops = 329.5 million acres in 1974; 335.0 million acres in 1978.

(2) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Source: Derived from Torgerson and Cooper, 1980.

and by commodity for each state during 1974. The information was obtained from Volume 1 of Energy and U.S. Agriculture: 1974 Data Base.

3. The same data source was then used to determine the ratio between total energy consumed by type for all crops grown in the state, and the amount of energy consumed by type that could be attributed to the specific crops under investigation in that state. For example, the data revealed that in Ohio approximately 40 percent of the total gasoline consumed for crop production in 1974 was utilized for corn; 38 percent of the diesel fuel; 76 percent of the LP gas; etc.

4. Volume 2 of the 1974 data base was then used to obtain an overview, on an aggregated national basis, of the amounts and type of energy used, by operation, for each of the crops being investigated in 1974. The operations were preplant, plant, cultivate, harvest, irrigate, etc.

5. The information from the preceding steps was then analyzed, tabulated, and the results used to provide a reasonable indication of the energy consumed, by type and operation, for each of the selected states and crops during 1974.

6. In order to update and project the 1974 data to 1978, the aforementioned USDA study providing 1978 data (Torgerson and Cooper, 1980) and USDA's annual summary of crop production for 1978 were reviewed. Using the information from these sources, the total amount of energy consumed in 1978 was estimated by type and crop for each of the selected states. The estimates were based upon the ratios developed in Step 3 above, augmented by best judgment decisions which included such factors as trends in energy conservation, shifts in fuel utilization, more efficient equipment, and changes in the number of acres planted to a crop.

7. Finally, the totals developed during the previous step were prorated by operation (preplant, plant, cultivate, etc.). These estimates were based upon data from the 1974 tables. Using all of the previously developed information as a basis, tables were created containing estimated 1978 consumption of energy for each of the selected crops and states.

The estimates of total agricultural energy used per acre by crop for selected states are summarized in Exhibit A-3 and presented in more detail in Exhibits A-4 through A-18. The crops, in sequence, are: corn, grain sorghum, winter wheat, barley, and oats. The first state indicated for each crop is a state having low energy utilization per bushel, followed by medium and high energy utilization states.

In Exhibit A-3, the estimates of total agricultural energy used are compared to the energy content of the ethanol produced. To offset the possible effects of unusually high crop yields for 1978, the latter estimates are based on three-year average yields for 1977-1979. It can be seen that, for each crop, substantial differences exist in agricultural energy requirements, primarily as a result of irrigation requirements. In Arizona (grain sorghum) and New Mexico (barley) the energy required to grow the grains exceeds the energy content of the ethanol produced (without considering either the additional energy required for processing and distillation or the energy value of by-products). The energy of the ethanol, however, is in liquid form, while most of the energy consumed for production in these two states is in the form of natural gas or electricity.

The detailed breakdown shown in Exhibits A-4 through A-18 shows energy consumption by type of fuel and by type of operation. For energy invested in fertilizers, the levels required for production assumed in the USDA studies are:

Nitrogen	31,100 Btu per pound
Phosphate (P_2O_5)	5,560 Btu per pound
Potash (K_2O)	4,280 Btu per pound

Potential ethanol yield per acre is highest for corn and second highest for grain sorghum. The yields for the other three crops are appreciably lower because of lower grain yields per acre (particularly in the case of wheat) and (except for wheat) low weights per bushel. For commercial ethanol production, corn would appear to be the most attractive grain in areas which are suitable for corn production, and grain sorghum would appear to be most attractive in most other grain-growing areas.

EXHIBIT A-3: AGRICULTURAL ENERGY REQUIREMENTS AND ETHANOL YIELDS FOR SELECTED GRAINS AND SELECTED STATES

Grain and State	Total Agric. Energy Used per Acre (1) (M Btu/A)	1977-79 Avg. Grain Yield per Acre (2) (bu/A)	Total Agric. Energy Used per Bushel (Btu/bu)	Density of Grain (lbs/bu)	Ethanol Yield per Bushel (3) (gal/bu)	Ethanol Yield per Acre (gal/A)	Energy Content of Ethanol Yield per Acre (M Btu/A)
Corn				56	2.62		
Wisconsin	6,211	102	60,900			267	22,500
Nebraska	10,848	109	99,500			286	24,100
Kansas	17,088	105	162,700			275	23,200
Grain Sorghum				56	2.70		
Missouri	5,230	78	67,100			211	17,800
Texas	9,419	50	188,400			135	11,400
Arizona	38,688	76	509,100			205	17,300
Winter Wheat				60	2.74		
Nebraska	2,396	34	70,500			93	7,800
Kansas	2,659	32	83,100			88	7,400
Texas	4,430	25	177,200			69	5,800
Barley				48	2.05		
Ohio	1,726	50	34,500			103	8,700
Idaho	6,028	55	109,600			113	9,500
New Mexico	17,939	55	326,200			113	9,500
Oats				32	1.05		
Iowa	1,130	61	18,500			64	5,400
South Dakota	1,368	50	27,400			53	4,500
Texas	2,387	38	62,800			40	3,400

Sources:

(1) Derived from USDA (1976, 1977) and Torgerson and Cooper (1980) (see text).
(2) USDA, 1978c, 1979b and 1980b.
(3) USDA, 1980a.

EXHIBIT A-4: ENERGY CONSUMPTION OF CORN IN WISCONSIN (1978)
(a low-energy state)

Operations	Motor Gasoline (Petroleum Products)	Distillate (Petroleum Products)	Residual Fuel (Petroleum Products)	LP Gas (Petroleum Products)	Natural Gas	Electricity	Invested Energy (1)	Total Energy of Identified Petroleum Products (2)	Total Energy (3)
Preplant	130 M gal	8,695 M gal		1 M gal				1,234 B Btu	1,234 B Btu
Plant	816	2,550		2				459	459
Cultivate	56	2,319		1				332	332
Harvest	11,732	4,734		43				2,133	2,133
Farm Pickup	6,157	6						770	770
Fertilizer Appl.	484	305		2				103	103
Pesticide Appl.	68	1,150						170	170
Farm Truck	5,917	2						740	740
Farm Auto	4,047							506	506
Grain Handling	89							11	11
Crop Drying				10,510		5 MM kwhr		998	1,050
Irrigation	86	388				24		65	315
Fertilizer							9,505 B Btu		9,505
Pesticides							678		678
Electricity						18			187
Miscellaneous	89	55		10,562				19	19
	29,673 M gal	20,203 M gal		10,562 M gal		47 MM kwhr	10,183 B Btu	7,540 B Btu	18,212 B Btu
CONSUMPTION PER ACRE	10.1 gal	6.9 gal		3.6 gal		16 kwhr	3,473 M Btu	2,571 M Btu	6,211 M Btu

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.

(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).

(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

EXHIBIT A-5: ENERGY CONSUMPTION OF CORN IN NEBRASKA (1978)
(a medium-energy state)

	Petroleum Products								
Operations	Motor Gasoline	Distillate	Residual Fuel	LP Gas	Natural Gas	Electricity	Invested Energy (1)	Total Energy of Identified Petroleum Products (2)	Total Energy (3)
Preplant	269 M gal	13,704 M gal		183 M gal				1,970 B Btu	1,970 B Btu
Plant	34	3,108		12				441	441
Cultivate	47	5,664		24				801	801
Harvest	8,404	22,279		5,225				4,666	4,666
Farm Pickup	23,347							2,918	2,918
Fertilizer Appl.	121	1,006		73				163	163
Pesticide Appl.	67	1,111		24				166	166
Farm Truck	16,606							2,076	2,076
Farm Auto	14,297							1,787	1,787
Grain Handling	626							78	78
Crop Drying				30,145	2 MM cu ft	21 MM kwhr		2,864	3,084
Irrigation	2,519	22,640		86,100	2,538	682		11,664	21,346
Fertilizer							31,118 B Btu		31,118
Pesticides							1,542		1,542
Electricity						61			634
Miscellaneous	1,003	335						172	172
	67,342 M gal	69,847 M gal		121,800 M gal	2,540 MM cu ft	765 MM kwhr	32,660 B Btu	29,766 B Btu	72,962 B Btu
CONSUMPTION PER ACRE	10.0 gal	10.3 gal		18.0 gal	376 cu ft	113 kwhr	4,830 M Btu	4,426 M Btu	10,848 M Btu

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

EXHIBIT A-6: ENERGY CONSUMPTION OF CORN IN KANSAS (1978)
(a high-energy state)

Operations	Petroleum Products: Motor Gasoline	Petroleum Products: Distillate	Petroleum Products: Residual Fuel	Petroleum Products: LP Gas	Natural Gas	Electricity	Invested Energy (1)	Total Energy of Identified Petroleum Products (2)	Total Energy (3)
Preplant	18 M gal	7,617 M gal		65 M gal				1,075 B Btu	1,075 B Btu
Plant		2,112						296	296
Cultivate		1,267						177	177
Harvest	2,050	3,450		3,147				1,038	1,038
Farm Pickup	5,421							678	678
Fertilizer Appl.	9	338		22				51	51
Pesticide Appl.	10	212		15				32	32
Farm Truck	2,326							291	291
Farm Auto	2,845							356	356
Grain Handling	75							9	9
Crop Drying				7,636		8 MM kwhr		725	809
Irrigation	230	1,125		8,925	9,540 MM cu ft	42		1,034	11,202
Fertilizer							8,923 B Btu		8,923
Pesticides							372		372
Electricity						31			322
Miscellaneous									
	12,984 M gal	16,121 M gal		19,810 M gal	9,540 MM cu ft	81 MM kwhr	9,295 B Btu	5,762 B Btu	25,631 B Btu
CONSUMPTION PER ACRE	8.6 gal	10.7 gal		13.2 gal	6,360 cu ft	54 kwhr	6,196 M Btu	3,841 M Btu	17,088 M Btu

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

EXHIBIT A-7: ENERGY CONSUMPTION OF GRAIN SORGHUM IN MISSOURI (1978)
(a low-energy state)

Operations	Motor Gasoline (Petroleum Products)	Distillate (Petroleum Products)	Residual Fuel (Petroleum Products)	LP Gas	Natural Gas	Electricity	Invested Energy (1)	Total Energy of Identified Petroleum Products (2)	Total Energy (3)
Preplant	184 M gal	2,500 M gal		45 M gal				377 B Btu	377 B Btu
Plant	85	870		20				134	134
Cultivate	90	990		28				153	153
Harvest	1,940	1,135		290				429	429
Farm Pickup	3,080							385	385
Fertilizer Appl.	145	20		29				24	24
Pesticide Appl.	96	70		30				25	25
Farm Truck	1,430							179	179
Farm Auto	1,200							150	150
Grain Handling	48							6	6
Crop Drying				1,890	5 MM cu ft	2 MM kwhr		180	205
Irrigation	70	90		180				38	38
Fertilizer							2,516 B Btu		2,516
Pesticides							140		140
Electricity						10			104
Miscellaneous									
	8,368 M gal	5,675 M gal		2,512 M gal	5 MM cu ft	12 MM kwhr	2,656 B Btu	2,080 B Btu	4,865 B Btu
CONSUMPTION PER ACRE	9.0 gal	6.1 gal		2.7 gal	5.4 cu ft	12.9 kwhr	2,859 M Btu	2,236 M Btu	5,230 M Btu

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

EXHIBIT A-8: ENERGY CONSUMPTION OF GRAIN SORGHUM IN TEXAS (1978)
(a medium-energy state)

Operations	Motor Gasoline (Petroleum Products)	Distillate (Petroleum Products)	Residual Fuel (Petroleum Products)	LP Gas (Petroleum Products)	Natural Gas	Electricity	Invested Energy (1)	Total Energy of Identified Petroleum Products (2)	Total Energy (3)
Preplant	986 M gal	35,230 M gal		980 M gal				5,149 B Btu	5,149 B Btu
Plant	23	10,177		54				1,433	1,433
Cultivate	47	8,232		81				1,166	1,166
Harvest	6,198	5,970		3,640				1,956	1,956
Farm Pickup	14,810							1,851	1,851
Fertilizer Appl.	42	238		51				43	43
Pesticide Appl.	1,174	215		566				231	231
Farm Truck	7,922	32						995	995
Farm Auto	8,265							1,033	1,033
Grain Handling	22							3	3
Crop Drying				565	29 MM cu ft	2 MM kwhr		54	104
Irrigation	2,019	2,467		10,800	18,791	420		1,624	25,159
Fertilizer							12,078 B Btu		12,078
Pesticides							2,082		2,082
Electricity						39			406
Miscellaneous									
	41,490 M gal	62,561 M gal		16,737 M gal	18,820 MM cu ft	461 MM kwhr	14,160 B Btu	15,538 B Btu	53,689 B Btu
CONSUMPTION PER ACRE	7.2 gal	10.9 gal		2.9 gal	3,301 cu ft	81 kwhr	2,484 M Btu	2,726 M Btu	9,419 M Btu

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

EXHIBIT A-9: ENERGY CONSUMPTION OF GRAIN SORGHUM IN ARIZONA (1978)
(a high-energy state)

	Petroleum Products								
Operations	Motor Gasoline	Distillate	Residual Fuel	LP Gas	Natural Gas	Electricity	Invested Energy (1)	Total Energy of Identified Petroleum Products (2)	Total Energy (3)
Preplant		395 M gal						55 B Btu	55 B Btu
Plant		60						8	8
Cultivate		136						19	19
Harvest	22 M gal	93		13 M gal				17	17
Farm Pickup	153							19	19
Fertilizer Appl.		44						6	6
Pesticide Appl.		6						1	1
Farm Truck	54							7	7
Farm Auto	50							6	6
Grain Handling				4				*	*
Crop Drying									
Irrigation					1,017 MM cu ft	140 MM kwhr			2,493
Fertilizer							395 B Btu		395
Pesticides							36		36
Electricity						3			31
Miscellaneous		11						2	2
	279 M gal	734 M gal		17 M gal	1,017 MM cu ft	143 MM kwhr	431 B Btu	140 B Btu	3,095 B Btu
CONSUMPTION PER ACRE	3.4 gal	9.1 gal		0.2 gal	12,712 cu ft	1,787 kwhr	5,387 M Btu	1,750 M Btu	38,688 M Btu

*Less than 0.5 B Btu.

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

EXHIBIT A-10: ENERGY CONSUMPTION OF WINTER WHEAT IN NEBRASKA (1978)
(a low-energy state)

Operations	Motor Gasoline	Distillate	Residual Fuel	LP Gas	Natural Gas	Electricity	Invested Energy (1)	Total Energy of Identified Petroleum Products (2)	Total Energy (3)
	Petroleum Products								
Preplant	93 M gal	3,370 M gal		2 M gal				484 B Btu	484 B Btu
Plant	24	2,000						283	283
Cultivate									
Harvest	2,936	5,160		63				1,095	1,095
Farm Pickup	7,150							894	894
Fertilizer Appl.	47	240						39	39
Pesticide Appl.	22	258						39	39
Farm Truck	4,802							600	600
Farm Auto	3,980							498	498
Grain Handling	211							26	26
Crop Drying				368				35	35
Irrigation	870	5,575		1,042	10 MM cu ft	15 MM kwhr		988	1,154
Fertilizer							1,691 B Btu		1,691
Pesticides							89		89
Electricity						2			21
Miscellaneous									
	20,135 M gal	16,603 M gal		1,475 M gal	10 MM cu ft	17 MM kwhr	1,780 B Btu	4,981 B Btu	6,948 B Btu
CONSUMPTION PER ACRE	6.9 gal	5.7 gal		0.5 gal	3.4 cu ft	5.8 kwhr	614 M Btu	1,718 M Btu	2,396 M Btu

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

EXHIBIT A-11: ENERGY CONSUMPTION OF WINTER WHEAT IN KANSAS (1978)
(a medium-energy state)

	Petroleum Products								
Operations	Motor Gasoline	Distillate	Residual Fuel	LP Gas	Natural Gas	Electricity	Invested Energy (1)	Total Energy of Identified Petroleum Products (2)	Total Energy (3)
Preplant	80 M gal	33,970 M gal		17 M gal				4,767 B Btu	4,767 B Btu
Plant		9,679						1,355	1,355
Cultivate									
Harvest	8,760	12,800		1,392				3,019	3,019
Farm Pickup	26,500							3,313	3,313
Fertilizer Appl.	40	1,124						162	162
Pesticide Appl.	45	685						102	102
Farm Truck	15,170							1,896	1,896
Farm Auto	13,224							1,653	1,653
Grain Handling	324							41	41
Crop Drying				2,004		6 MM kwhr		190	253
Irrigation	983	3,560		2,484	1,222 MM cu ft	33		857	2,447
Fertilizer							10,407 B Btu		10,407
Pesticides							375		375
Electricity						25			260
Miscellaneous									
	65,126 M gal	61,818 M gal		5,897 M gal	1,222 MM cu ft	64 MM kwhr	10,782 B Btu	17,355 B Btu	30,050 B Btu
CONSUMPTION PER ACRE	5.7 gal	5.4 gal		0.5 gal	108 cu ft	5.6 kwhr	954 M Btu	1,536 M Btu	2,659 M Btu

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

EXHIBIT A-12: ENERGY CONSUMPTION OF WINTER WHEAT IN TEXAS (1978)
(a high-energy state)

	Petroleum Products								
Operations	Motor Gasoline	Distillate	Residual Fuel	LP Gas	Natural Gas	Electricity	Invested Energy (1)	Total Energy of Identified Petroleum Products (2)	Total Energy (3)
Preplant	626 M gal	23,618 M gal		539 M gal				3,436 B Btu	3,436 B Btu
Plant	15	5,950		12				836	836
Cultivate									
Harvest	4,350	2,909		3,204				1,255	1,255
Farm Pickup	10,703			1,028				1,436	1,436
Fertilizer Appl.	24	102		12				18	18
Pesticide Appl.	550	95		578				137	137
Farm Truck	5,665	17						711	711
Farm Auto	5,247							656	656
Grain Handling	14							2	2
Crop Drying				210	8 MM cu ft	1 MM kwhr		20	39
Irrigation	1,283	1,198		4,397	8,375	197		746	11,337
Fertilizer							4,251 B Btu		4,251
Pesticides							727		727
Electricity						19			198
Miscellaneous	1,338	341						215	215
	29,815 M gal	34,230 M gal		9,980 M gal	8,383 MM cu ft	217 MM kwhr	4,978 B Btu	9,468 B Btu	25,254 B Btu
CONSUMPTION PER ACRE	5.2 gal	6.0 gal		1.7 gal	1,470 cu ft	38 kwhr	873 M Btu	1,661 M Btu	4,430 M Btu

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

EXHIBIT A-13: ENERGY CONSUMPTION OF BARLEY IN OHIO (1978)
(a low-energy state)

Operations	Motor Gasoline	Distillate	Residual Fuel	LP Gas	Natural Gas	Electricity	Invested Energy (1)	Total Energy of Identified Petroleum Products (2)	Total Energy (3)
	Petroleum Products								
Preplant	1 M gal	9 M gal						1 B Btu	1 B Btu
Plant	1	6						1	1
Cultivate									
Harvest	9	8						2	2
Farm Pickup	20							3	3
Fertilizer Appl.									
Pesticide Appl.									
Farm Truck	9							1	1
Farm Auto	10							1	1
Grain Handling									
Crop Drying				14 M gal				1	1
Irrigation									
Fertilizer							8 B Btu		8
Pesticides							1		1
Electricity									
Miscellaneous									
	50 M gal	23 M gal		14 M gal			9 B Btu	10 B Btu	19 B Btu
CONSUMPTION PER ACRE	4.5 gal	2.1 gal		1.2 gal				908 M Btu	1,726 M Btu

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

EXHIBIT A-14: ENERGY CONSUMPTION OF BARLEY IN IDAHO (1978)
(a medium-energy state)

	Petroleum Products								
Operations	Motor Gasoline	Distillate	Residual Fuel	LP Gas	Natural Gas	Electricity	Invested Energy (1)	Total Energy of Identified Petroleum Products (2)	Total Energy (3)
Preplant	38 M gal	1,295 M gal		12 M gal				187 B Btu	187 B Btu
Plant	12	510		2				73	73
Cultivate				2				*	*
Harvest	667	1,258		100				269	269
Farm Pickup	826							103	103
Fertilizer Appl.	16	207		2				31	31
Pesticide Appl.		213						30	30
Farm Truck	444	140						75	75
Farm Auto	429							54	54
Grain Handling	15							2	2
Crop Drying									
Irrigation	513	77		471	53 MM cu ft	327 MM kwhr		120	3,575
Fertilizer							1,185 B Btu		1,185
Pesticides							91		91
Electricity						5			52
Miscellaneous									
	2,960 M gal	3,700 M gal		589 M gal	53 MM cu ft	332 MM kwhr	1,276 B Btu	944 B Btu	5,727 B Btu
CONSUMPTION PER ACRE	3.1 gal	3.9 gal		0.6 gal	56 cu ft	349 kwhr	1,343 M Btu	994 M Btu	6,028 M Btu

*Less than 0.5 B Btu.

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

EXHIBIT A-15: ENERGY CONSUMPTION OF BARLEY IN NEW MEXICO (1978)
(a high-energy state)

Operations	Petroleum Products: Motor Gasoline	Petroleum Products: Distillate	Petroleum Products: Residual Fuel	Petroleum Products: LP Gas	Natural Gas	Electricity	Invested Energy (1)	Total Energy of Identified Petroleum Products (2)	Total Energy (3)
Preplant	1 M gal	112 M gal						16 B Btu	16 B Btu
Plant		19						3	3
Cultivate									
Harvest	15	49		6 M gal				9	9
Farm Pickup	50							6	6
Fertilizer Appl.		3						*	*
Pesticide Appl.		2						*	*
Farm Truck	19							2	2
Farm Auto	46							6	6
Grain Handling									
Crop Drying									
Irrigation	134	217		370	325 MM cu ft	9 MM kwhr		82	507
Fertilizer							38 B Btu		38
Pesticides							5		5
Electricity									
Miscellaneous									
	265 M gal	402 M gal		376 M gal	325 MM cu ft	9 MM kwhr	43 B Btu	124 B Btu	592 B Btu
CONSUMPTION PER ACRE	8.0 gal	12.2 gal		11.3 gal	9,848 cu ft	273 kwhr	1,303 M Btu	3,757 M Btu	17,939 M Btu

*Less than 0.5 B Btu.

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

EXHIBIT A-16: ENERGY CONSUMPTION OF OATS IN IOWA (1978)
(a low-energy state)

	Petroleum Products								
Operations	Motor Gasoline	Distillate	Residual Fuel	LP Gas	Natural Gas	Electricity	Invested Energy (1)	Total Energy of Identified Petroleum Products (2)	Total Energy (3)
Preplant	93 M gal	1,304 M gal		29 M gal				197 B Btu	197 B Btu
Plant	98	345		118				72	72
Cultivate									
Harvest	1,490	644		587				332	332
Farm Pickup	3,015							377	377
Fertilizer Appl.	88			12				12	12
Pesticide Appl.	57			23				9	9
Farm Truck	1,433							179	179
Farm Auto	802							100	100
Grain Handling	51							6	6
Crop Drying				348		1 MM kwhr		33	43
Irrigation	7	7		58		1		7	18
Fertilizer							439 B Btu		439
Pesticides							5		5
Electricity						7			73
Miscellaneous	29							4	4
	7,165 M gal	2,300 M gal		1,175 M gal		9 MM kwhr	444 B Btu	1,328 B Btu	1,866 B Btu
CONSUMPTION PER ACRE	4.3 gal	1.4 gal		0.7 gal		5.5 kwhr	269 M Btu	804 M Btu	1,130 M Btu

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

EXHIBIT A-17: ENERGY CONSUMPTION OF OATS IN SOUTH DAKOTA (1978)
(a medium-energy state)

	Petroleum Products								
Operations	Motor Gasoline	Distillate	Residual Fuel	LP Gas	Natural Gas	Electricity	Invested Energy (1)	Total Energy of Identified Petroleum Products (2)	Total Energy (3)
Preplant	60 M gal	2,338 M gal		5 M gal				325 B Btu	325 B Btu
Plant	102	849						132	132
Cultivate									
Harvest	1,343	2,890		73				579	579
Farm Pickup	4,878			1				610	610
Fertilizer Appl.	36	67						14	14
Pesticide Appl.	34	53		53				12	12
Farm Truck	2,099							262	262
Farm Auto	1,819							227	227
Grain Handling	239							30	30
Crop Drying				201				19	19
Irrigation	238	171		143		5 MM kwhr		67	119
Fertilizer							999 B Btu		999
Pesticides							11		11
Electricity						10			104
Miscellaneous	505							63	63
	11,353 M gal	6,368 M gal		423 M gal		15 MM kwhr	1,010 B Btu	2,350 B Btu	3,516 B Btu
CONSUMPTION PER ACRE	4.2 gal	2.5 gal		0.2 gal		5.8 kwhr	393 M Btu	914 M Btu	1,368 M Btu

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

EXHIBIT A-18: ENERGY CONSUMPTION OF OATS IN TEXAS (1978)
(a high-energy state)

	Petroleum Products								
Operations	Motor Gasoline	Distillate	Residual Fuel	LP Gas	Natural Gas	Electricity	Invested Energy (1)	Total Energy of Identified Petroleum Products (2)	Total Energy (3)
Preplant	138 M gal	5,899 M gal		55 M gal				848 B Btu	848 B Btu
Plant	4	1,874		2				263	263
Cultivate									
Harvest	899	1,227		247				308	308
Farm Pickup	2,419							302	302
Fertilizer Appl.	6	30		1				5	5
Pesticide Appl.	165	26		30				27	27
Farm Truck	1,285							161	161
Farm Auto	1,995							249	249
Grain Handling	3							*	*
Crop Drying									
Irrigation	241	589		167		7 MM kwhr		128	201
Fertilizer							1,845 B Btu		1,845
Pesticides							37		37
Electricity						1			10
Miscellaneous		300						42	42
	7,155 M gal	9,945 M gal		502 M gal		8 MM kwhr	1,882 B Btu	2,333 B Btu	4,298 B Btu
CONSUMPTION PER ACRE	3.9 gal	5.5 gal		0.3 gal		4.4 kwhr	1,045 M Btu	1,296 M Btu	2,387 M Btu

*Less than 0.5 B Btu.

(1) "Invested energy" consists of all energy required to produce and transport fertilizer and pesticides to the farm gate.
(2) Excludes energy of petroleum products used for producing and transporting fertilizer and pesticides (see preceding footnote).
(3) Based on Btu conversion factors stated at front of this volume. Energy required for electricity estimated as 10,400 Btu coal per kwhr of electricity.

Sources: Derived from USDA (1976 and 1977) and Torgerson and Cooper (1980) (see text).

A.2 The Effect of Ethanol Production on Agricultural Energy Consumption

Estimates of the effect of ethanol production on agricultural energy consumption were obtained from an interregional linear programming model of agricultural production developed at Iowa State University (ISU) (Dvoskin and Heady, 1976; Turhollow, 1982; and Turhollow, Christensen and Heady, forthcoming). This model was selected because of its unique capabilities for estimating the effects of ethanol production on the demand for feed crops and on agricultural energy consumption.

In the model, the United States is divided into 28 market regions which are further divided into 105 producing areas. The model determines agricultural production levels and resource usage by production area in order to satisfy, at minimum cost, a set of demands which are exogenously specified by market region. These demands include domestic and export demand for beef, pork, milk, alcohol, wheat and cotton, and export and nonfeed domestic demand for nine feed crops. Prices of all farm resources except land and water are specified exogenously; these specifications include the price of diesel fuel, LPG, natural gas and electricity, by producing area. The cost and fuel requirements of interregional transport are also specified exogenously, but intraregional transport is not considered. For each producing area, potential crop yields are specified as a function of crops planted, number of crops per year, fertilizer utilization, tillage practice, and, in the western United States, irrigation.

Alcohol production is an exogenously specified activity which results in the consumption of corn and/or grain sorghum and the production of by-products which may substitute for soybean exports or for soybeans, corn or grain sorghum consumed by domestic livestock. For each market region, the model determines whether wet or dry-milling will be used for alcohol production on the basis of the cost of the two technologies and the endogenously estimated value of the by-products of the two processes.

For a given set of exogenous variables, the model determines the least cost means of satisfying the specified agricultural demands. Each model solution includes specifications of production, yield, value and cost of production, by crop and producing area; and use of land, water, fertilizer (by type), pesticides and energy, by producing area. Four sources of energy are distinguished: electricity, natural gas, LPG, and other petroleum products; this last category is primarily diesel fuel (and is called "diesel fuel" by the model), but it also includes some gasoline and residual fuel.

The first subsection below describes the use of this model for estimating the effect of ethanol production on agricultural energy consumption. The estimates presented in this subsection are the ones used in the body of this report. The second subsection discusses the sensitivity of these estimates to the assumptions used in their development and to potential changes in the agricultural production system.

A.2.1 Increased Energy Consumption

The estimates of the effect of ethanol production on agricultural energy consumption were obtained by comparing the results of two solutions produced by the ISU Model. The two runs differed only in that it was assumed that no grain would be used for ethanol in the "base-case" run, while, in the second run, six billion gallons of ethanol would be produced from corn and grain sorghum.[1] All ethanol production was assumed to occur in corn-producing areas. An ethanol yield of 2.58 gallons per bushel of corn or grain sorghum was assumed as required by the conversion technology described in Appendix B. In both runs, exogenous specifications of agricultural yields, energy prices, and all exports except cotton were set to their 1981 values. A five-year average (for 1977-1981) was used for all domestic consumption and for exports of cotton. An estimated 378 million acres of cropland was available in 1981 for producing the eleven crops considered by the model.

A summary of agricultural production in the two runs is presented in Exhibit A-19. Slightly more than 2.3 billion bushels of corn and grain sorghum are required to produce six billion gallons of ethanol. The model indicates that, under the conditions specified, nearly 20 percent of the grain will be grain sorghum. Grain sorghum is used in the Kansas City and Denver market regions (which include all of Nebraska and parts of the adjoining states), while corn is used throughout most of the remainder of the Corn Belt. The estimate that some grain sorghum will be used for ethanol production differs from that of previous runs of the model (see Section A.2.2, below) which indicated that all the ethanol would be produced from corn.

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[1] *The level of ethanol production was selected to be consistent with that used by ISU in previous analyses (see Section A.2.2). The assumed production level of six billion gallons per year would permit production of 60 billion gallons of gasohol containing ten percent ethanol by volume. This level of fuel production compares to 101 billion gallons of gasoline and gasohol consumed in 1981.*

EXHIBIT A-19: EFFECT OF ETHANOL PRODUCTION ON AGRICULTURAL PRODUCTION

	Base Case	Grain Used for 6 B Gal Ethanol	Change	Percent Change
<u>Feed Grains</u>				
Corn	6,793 MM bu	8,632 MM bu	+1,839 MM bu	+27.0%
—for ethanol	—	1,899 "	+1,899 "	—
Sorghum	737 "	1,067 "	+330 "	+44.8%
—for ethanol	—	429 "	+429 "	—
Barley	375 "	382 "	+7 "	+1.2%
Oats	229 "	258 "	+29 "	+12.7%
<u>Other Crops</u>				
Wheat	2,295 "	2,274 "	-21 "	-0.9%
Soybeans	2,079 "	1,613 "	-466 "	-22.4%
Cotton	12,549 M bales	12,549 M bales	—	—
Hay	79 MM tons	75 MM tons	-4 MM tons	-5.1%
Silage	237 "	231 "	-6 "	-2.5%
<u>Ethanol By-Products</u>				
Gluten Feed	—	208 MM cwt	+208 MM cwt	—
Gluten Meal (42% protein)	—	121 "	+121 "	—
Vegetable Oil	—	33.5 "	+33.5 "	—

Source: ISU Model

The model indicates that all ethanol production will use wet milling. As shown in Exhibit A-19, the by-products consist of 208 million cwt of gluten feed, 121 million cwt of gluten meal, and 33.5 million cwt of vegetable oil.[1] The availability of gluten feed and gluten meal results in reduced demand for soybeans and, to a lesser extent, reduced demand for corn and grain sorghum. As a result, soybean production falls by 22 percent (466 million bushels per year), while the overall increase in corn and grain sorghum production is somewhat less than it would have been if feed use of these two crops did not change. Nonetheless, corn production rises by 27 percent (1.8 billion bushels per year) and grain-sorghum production by 45 percent (330 million bushels per year). Some minor adjustments also occur in the production of other crops, as shown in Exhibit A-19.

The estimated effect of these crop production changes on use of land, fertilizer and pesticides, is summarized in Exhibit A-20. Because corn yields per acre are about three times as high as soybean yields, much of the increase in the production can be accomplished by shifting land from soybeans to corn or grain sorghum. For this reason, large increases in production of these two crops are obtained with only a 2.4 percent increase in total land used (8.3 million acres). However, the estimated increase in land which is irrigated (an energy-consuming procedure) is 14.6 percent (2.6 million acres). Use of nitrogen fertilizer, an energy-intensive product which is required for growing corn and grain sorghum, but not soybeans, also rises significantly (by 23 percent).

The energy requirements for crop production with and without ethanol production are summarized in Exhibits A-21 and A-22. The former exhibit displays energy requirements by use and source estimated by the model for base-case conditions. As previously observed, the model's estimate of "diesel fuel" consumption includes unspecified (but relatively small) amounts of gasoline and residual fuel. The largest energy consumers are seen to be machinery (which is entirely diesel fuel), pesticide production, and production of nitrogen fertilizers (primarily natural gas).

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[1] *The gluten meal in the model is actually a mixture of gluten meal and gluten feed and has a lower protein content (42 percent) than the 60 percent protein gluten meal produced by the milling process itself. For ethanol produced from corn, the combined production of gluten meal and gluten feed, the combined protein content of these two products, and the production of corn oil, are the same per gallon as that produced by the wet-milling process described in Section B.2.2 of Appendix B. For ethanol produced from grain sorghum, gluten meal and gluten feed production are appropriately adjusted to reflect the higher protein content of the grain sorghum, and oil production is appreciably lower than when corn is used.*

EXHIBIT A-20: EFFECT OF ETHANOL PRODUCTION ON USAGE OF AGRICULTURAL RESOURCES

	Base Case	Grain Used for 6 B Gal Ethanol	Change	Percent Change
Land Used				
Unirrigated	322,601 M A	328,305 M A	5,704 M A	+1.8%
Irrigated	17,855 "	20,469 "	2,614 "	+14.6%
	340,456 M A	348,774 M A	8,318 M A	+2.4%
Fertilizer				
Nitrogen	11,599 MM lb	14,290 MM lb	2,691 MM lb	+23.2%
Potassium	5,876 "	6,234 "	358 "	+6.1%
Phosphorous	3,849 "	4,141 "	292 "	+7.6%
Pesticides	1,939 "	2,069 "	130 "	+6.7%

Source: ISU Model

EXHIBIT A-21: BASE-CASE ENERGY CONSUMPTION

	Petroleum Products				
Use	Diesel Fuel (MM gal)	LPG (MM gal)	Natural Gas (B cu ft)	Electricity (MM kwhr)	Total Energy (T Btu)
Machinery	3,685.9				516.0
Irrigation	67.5	57.2	12.4	7,843.1	109.2
Crop Drying		616.1			58.5
Nitrogen Fertilizers			282.1	753.9	295.6
Nonnitrogen Fertilizers			12.3	2,046.8	33.9
Pesticides	617.8		99.4	17,881.8	374.0
Transportation	642.7				90.0
	5,013.9	673.3	406.2	28,525.6	1,477.2

Source: ISU Model

EXHIBIT A-22: INCREMENTAL ENERGY CONSUMPTION

	Petroleum Products						
Use	Gasoline (MM gal)	Diesel Fuel (MM gal)	LPG (MM gal)	Natural Gas (B cu ft)	Electricity (MM kwhr)	Total Energy (T Btu)	Percent Change from Base Case
Machinery		172.5				24.2	+4.7%
Irrigation		20.1	18.9	11.2	1,128.6	27.8	+25.4
Crop Drying			121.9			11.6	+19.8
Nitrogen Fertilizers				65.5	175.0	68.6	+23.2
Nonnitrogen Fertilizers				0.9	39.6	1.3	+3.9
Pesticides		30.1		10.4	895.6	24.1	+6.5
Transportation[1]	20.7	-49.2				-4.3	-4.8
	20.7	173.5	140.8	88.0	2,238.8	153.3	+10.4
Percent Change from Base Case	—	+3.5%	+20.9%	+21.7%	+7.8%	+10.4%	

(1) Includes estimate of fuel consumed due to increased intraregional transport of crops and increased transport of fertilizer (see text).

Source: ISU Model and supplementary estimates of effects on transportation fuel consumption (see text).

The latter exhibit (A-22) shows the change in energy consumption between the base-case run and the ethanol-production run. The largest increase in amount of energy consumed (69 trillion Btu) is for the production of nitrogen fertilizers, but significant increases also occur in energy consumed for irrigation, machinery and pesticide production. The increase in energy consumed in drying crops (which is entirely supplied by LPG) is somewhat smaller in absolute terms, but represents a 20 percent increase in this use.

All data shown in Exhibit A-22 were obtained from a comparison of the two runs of the model, with the exception of data for transportation energy use. The model considers only interregional transport of agricultural products and ethanol by-products, but not local transport of agricultural products or fertilizer. The model indicates that a moderate reduction in interregional transportation energy requirements will occur as exports of soybeans are replaced, in part, by exports of the by-product gluten meal. A reduction of 85.7 million gallons of diesel fuel for interregional transport of crops is indicated by the model, balanced in part by 20.1 million gallons required for transport of the by-products.

The resulting saving in transportation fuel, though relatively modest in comparison to overall energy requirements, is overstated since the increases in local transport required as a result of increased production and marketing of crops is not reflected in the model's results. To capture this effect, an estimate of fuel consumed in intraregional transport was developed and incorporated into the results shown in the exhibit. In developing this estimate, it was assumed that feed grains, soybeans and wheat are transported an average of 25 miles intraregionally, and that half of this transport is provided by gasoline-powered vehicles and half by diesel-powered vehicles (including those pulled by farm tractors). It was further assumed that gasoline consumption could be estimated by assuming that the vehicles averaged 5.4 miles per gallon empty and 4.3 miles per gallon with a full 12-ton load, and that overall diesel fuel economy was 60 percent better (derived from Knapton, 1981, and Mergel, 1981). The resulting estimates of fuel used for intraregional transport of crops are 20.7 million gallons of gasoline and 13.0 million gallons of diesel fuel. In addition, it was estimated that transport of additional fertilizer (1.67 million tons) would require 3.4 million gallons of diesel fuel on the basis of assumptions incorporated into the analysis of Appendix D (see Exhibit D-4). These adjustments, which are incorporated into the results of Exhibit A-22, reduce the estimated saving in transport fuel by about half, but

they result in only a three percent increase in the estimate of total energy requirements shown in the exhibit and a fourteen percent increase in the estimate of petroleum products consumed.

The overall increase in energy consumption, 153.3 trillion Btu, represents increased energy consumption of 65,900 Btu for each bushel of grain used for ethanol conversion. This figure is similar in magnitude to the estimates presented in Section A.1, above, for average energy consumption for producing corn and grain sorghum in low-energy states (60,900 Btu per bushel for corn in Wisconsin, and 67,100 Btu per bushel for grain sorghum in Missouri). Unlike these average consumption figures, however, the 65,900 Btu figure reflects not only the energy required for increasing grain production, but also the energy saved as a result of the substitution of ethanol by-products for soybeans and other feed products. This latter saving is quite significant. A third run of the model (discussed separately in Section E.3.3 of Appendix E) indicates that the energy required for increasing production of corn without reducing the production of any other crop is 82,300 Btu per bushel, 35 percent higher than the estimated average consumption of 60,900 Btu per bushel in a low-energy state.

As previously observed, the model indicates that, under the conditions specified, nearly 20 percent of grain used for ethanol production would be grain sorghum. To determine the effect of restricting grain use to corn, a fourth run of the model was made in which this restriction was incorporated. This run indicates that, if only corn is used, increased energy consumption would be 157.9 trillion Btu,[1] about 3 percent higher than if both corn and grain sorghum are used; and that consumption of petroleum products would increase by 41.9 trillion Btu, about four percent more than if both grains are used.

The model also produces estimates of agricultural prices. Exhibit A-23 shows the effect on national average crop prices of using corn and grain sorghum to produce six billion gallons of ethanol. The increased agricultural production levels required to provide the ethanol feedstock result in moderate increases in the prices of most crops. The price of wheat is estimated to rise by nearly four percent, and the prices of some feed crops are estimated to rise by even more (by 8.5 percent and 11.7 percent for corn and grain sorghum, respectively). However, the effect on meat and milk prices (not shown in the exhibit) is negligible, with increases estimated to be less than one-

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[1] *This figure includes the modified estimate of transportation fuel requirements discussed above.*

EXHIBIT A-23: EFFECT OF ETHANOL PRODUCTION
ON AGRICULTURAL PRICES
(1975 dollars)

	Base Case	Grain Used for 6 B Gal Ethanol	Percent Change
Feed Grains			
Corn	$ 1.431/bu.	$ 1.553/bu.	+8.5%
Sorghum	1.291/bu.	1.442/bu.	+11.7%
Barley	1.264/bu.	1.263/bu.	-0.1%
Oats	1.019/bu.	1.109/bu.	+8.8%
Other Crops			
Wheat	$ 2.07/bu.	$ 2.15/bu.	+3.9%
Soybeans	3.22/bu.	3.32/bu.	+3.1%
Cotton	168.39/bale	170.37/bale	+1.2%
Hay	37.06/ton	38.02/ton	+2.6%
Silage	11.29/ton	11.52/ton	+2.0%

Source: ISU Model

twentieth of one percent; the small effect on meat and milk prices is due to the availability of the ethanol by-products for feed use and to the small portion of total livestock costs represented by feed costs.

In reviewing the above results, it should be observed that the effect of increased prices on demand is not considered by the model. Increased prices may result in some decrease in domestic consumption of wheat and cotton and in the export of feed products. (The insignificant effect on meat and milk prices would indicate that any effect on the total domestic demand for feed would be negligible.) Any decrease in domestic consumption may be presumed to represent a reduction in some aspect of general welfare; while any decrease in exports would have an adverse effect on our balance of trade. Such reductions in demand for agricultural products, however, would also result in somewhat smaller increases in production, in the consumption of energy and other resources, and in agricultural prices, than indicated in Exhibits A-19 through A-23.

A.2.2 Sensitivity of Results

In order to gain a better understanding of some of the factors affecting the results discussed in the preceding subsection, it is useful to compare these results to unpublished results produced by previous runs of the model. (These runs are described more fully in Turhollow, 1982.)

The earlier runs were performed using two alternative base cases representing conditions projected for the Year 2000. These two base cases are compared to the one used in the present study (using 1981 conditions) in Exhibit A-24. The Year 2000 base cases presume improved technology, greater agricultural productivity, increased agricultural demand, and substantially higher energy prices[1] than used in the present study. The two Year 2000 base cases differ in the level of agricultural exports assumed; they are accordingly identified as the low-export base case (or "2000L"), and the high-export base case (or "2000H").

It can be seen from Exhibit A-24 that, in the low-export base case, overall crop production and total land used are higher than in the 1981 base case, but use of irrigated land and nitrogen fertilizer is lower. These differences are the result of

[1] *Exhibit A-24 shows minor differences in the average prices of energy used in the two base cases for the Year 2000. These differences result from regional variations in energy prices and from differing regional distributions of agricultural energy consumption in the two base cases.*

EXHIBIT A-24: COMPARISON OF BASE CASES

	Units	Used in This Study	Used in Previous Studies: Low Exports	Used in Previous Studies: High Exports
Year Simulated		1981	2000	2000
Crop Production				
Corn	MM bu	6,793	7,398	8,780
Grain Sorghum	MM bu	737	676	654
Barley	MM bu	375	414	422
Oats	MM bu	229	295	280
Wheat	MM bu	2,295	2,784	3,147
Soybeans	MM bu	2,079	2,394	3,252
Cotton	M bales	12,549	13,840	13,840
Hay	MM tons	79	159	151
Silage	MM tons	237	386	411
Average Price of Energy				
Diesel Fuel	1975$/gal	$ 0.699	$ 1.189	$ 1.187
LPG	1975$/gal	$ 0.416	$ 0.726	$ 0.723
Natural Gas	1975$/Mcf	$ 1.998	$ 5.561	$ 5.530
Electricity	1975$/kwhr	$ 0.023	$ 0.046	$ 0.046
Land Used				
Unirrigated	M A	322,601	368,189	360,834
Irrigated	M A	17,855	11,342	28,235
		340,456	379,539	389,069
Fertilizer				
Nitrogen	MM lb	11,599	9,692	14,023
Potassium	MM lb	5,876	6,320	7,598
Phosphorus	MM lb	3,849	4,029	5,615
Pesticides	MM lb	1,939	3,279	3,730
Energy Consumption				
Diesel Fuel	MM gal	5,014	5,495	6,590
LPG	MM gal	673	691	980
Natural Gas	B cu ft	406	360	529
Electricity	MM kwhr	28,526	27,205	35,235
Total Energy	T Btu	1,477	1,485	1,922
Average Price				
Feed Grains	1975$/bu	$ 1.43	$ 1.54	$ 2.10
Soybeans	1975$/bu	$ 3.22	$ 3.46	$ 4.95
Wheat	1975$/bu	$ 2.07	$ 2.59	$ 3.92

Source: ISU Model

projected improvements in agricultural productivity, conversion of additional land to crop use over the next twenty years, and projected increases in the cost of energy (which tend to discourage the use of energy-intensive factors of production such as irrigation and nitrogen fertilizer). As a result, though production in 2000L is projected to be appreciably higher than in 1981, the model indicates that total energy consumption will be hardly any greater. The additional increases in production required in the high-export base case, however, result in a moderate increase in total land used (relative to the low-export case) and greater increases in the use of irrigation, nitrogen fertilizer, and total energy.

The earlier ISU work analyzed energy requirements for producing grain for conversion to ethanol under six alternative scenarios. The results of these analyses are presented in Exhibit A-25 along with a comparable summary of the results of the analysis performed for this study. For all seven analyses, the energy-consumption results shown in this exhibit were obtained directly from the model and do not reflect the adjustment to the model's transport energy estimates discussed in the previous subsection;[1] the energy requirements shown in Exhibit A-25 for the analysis used in this study (in the last column of the exhibit) are therefore slightly lower than those shown previously in Exhibit A-22 (in which transportation energy requirements have been adjusted).

The six earlier analyses consist of the three pairs of analyses differing in the base-case used (2000L or 2000H) and/or ethanol yield. Each of these pairs consists of two analyses differing in the volume of ethanol produced (three, six or twelve billion gallons annually). The yields assumed are 2.6 gallons of ethanol per bushel of grain and 3.0 gallons per bushel. The former yield is approximately the same as that used in the present study (2.58 gallons per bushel); while the latter yield presumes the use of new technology which would convert some cellulose to ethanol as well as the starches and sugars which are converted using conventional technologies. In the first four of these analyses, the model indicated that grain sorghum would be used for ten to twenty percent of the feedstock and corn for the remainder; in the last two analyses, the model indicated only corn would be used.

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[1] *The lack of an adjustment to the estimates of incremental transport energy result in underestimating the increase in diesel fuel and, in one case (3H3), in an indicated decline in diesel fuel consumption (due to a decline in interregional transport requirements).*

EXHIBIT A-25: COMPARISON OF ENERGY CONSUMPTION RESULTS

		Run Name						
		6L2	12L2	6L3	12L3	3H3	6H3	6P2
Base Case Used[1]		2000L	2000L	2000L	2000L	2000H	2000H	1981
Ethanol Production	B gal	6	12	6	12	3	6	6
Ethanol Yield	gal/bu	2.6	2.6	3	3	3	3	2.58
<u>Increased Energy Consumption</u>								
Diesel Fuel	MM gal	148.1	268.7	115.6	268.5	-20.2	80.4	137.0
LPG	MM gal	197.0	401.1	191.1	388.5	107.4	208.9	140.8
Natural Gas	B cu ft	54.0	121.9	50.2	114.7	56.9	101.0	88.0
Electricity	MM kwhr	2,497.1	3,437.5	2,285.8	3,316.5	1,258.8	1,877.2	2,238.8
Total Increased Energy	T Btu	120.5	235.8	109.3	226.0	78.5	153.6	145.6
Energy per Bushel of Grain Used	M Btu/bu	52.2	51.1	54.7	56.5	78.5	76.8	62.6
<u>Increased Prices</u>								
Feed Grains	percent	7.8%	16.9%	7.1%	14.9%	2.4%	5.7%	7.7%
Wheat	percent	5.4%	13.5%	5.4%	13.1%	2.0%	4.8%	3.9%

(1) Base Cases:
1981 - used in this study
2000L - simulation of year 2000 with low exports
2000H - simulation of year 2000 with high exports

Source: ISU Model. Energy consumption figures reflect reduced intraregional transport of grain but do not reflect any other changes in transport requirements.

A comparison of the energy-consumption estimates for the three pairs of analyses in Exhibit A-25 reveals one particularly interesting result: doubling the amount of ethanol to be produced (while holding all other specifications constant) results in an approximately proportional increase in total agricultural energy requirements. If one considers agricultural energy consumption per bushel of grain used for ethanol production, it is seen from the exhibit that, in two of the three pairs, increasing production actually results in a slight decrease in energy consumption per bushel. The decreases reflect the fact that the model attempts to minimize cost rather than energy consumption. These decreases indicate only that, under particular conditions, it is most economical to adapt to the first increments in demand using somewhat energy intensive means but to meet some additional increments using means which are less energy intensive. It is likely that further increments in demand (beyond those analyzed) would again require more energy-intensive responses (particularly as available land becomes increasingly tighter). The minor changes (both positive and negative) in energy required per bushel used for ethanol production resulting from increasing ethanol production cannot be considered significant. It can therefore be concluded that incremental agricultural energy required per bushel used appears to be relatively unaffected by the volume of ethanol produced (at least for annual volumes of no more than twelve billion gallons).

Although incremental agricultural energy consumption per bushel used appears to be relatively insensitive to the volume of ethanol produced, it is quite sensitive to the base-case conditions assumed. Scenarios 6L3 and 6H3 (Columns 3 and 6 of Exhibit A-25) differ only in the level of agricultural exports assumed. The higher exports of 6H3 result in a forty percent increase in incremental energy requirements per bushel! This difference results from substantial differences in land utilization under the two base cases. Under the low-export case, land for additional production is relatively available; but, under the high-export case, land is appreciably tighter and expanded production is obtained to a greater extent by increasing nitrogen fertilization and irrigation. It may be noted that increased use of natural gas (used primarily for producing nitrogen fertilizer) is twice as high under 6H3 as under 6L3.

The effect of base-case conditions on incremental agricultural energy consumption per bushel used can also be observed by comparing the results of the analyses used in this study (6P2) with the most similar of the earlier analyses: 6L2. Although 6L2 presumes higher base-case agricultural production (see the low-export column in Exhibit A-24), as a result of projected improvements in agricultural productivity and conversions of land

to crop uses, land is projected to be less tight under this base case than under the one used in the present study; and, of course, energy is expected to be substantially more expensive. Accordingly, incremental energy consumption is estimated to be twenty percent higher in 6P2 than in 6L2, and consumption of natural gas is over sixty percent higher.

The effect of ethanol yield on incremental agricultural energy consumption is also shown in Exhibit A-25. Increasing the yield from 2.6 gallons per bushel to 3.0 results in some decrease in agricultural energy required, but a five to ten percent increase in incremental agricultural energy required per bushel of grain used. The latter effect is due primarily to the reduced yields of feed by-products per bushel that would result when ethanol yields per bushel are increased.

Exhibit A-25 also displays data on the effect of ethanol production on the average prices of feed grains and wheat. It can be seen from these data that, although, for the analyses performed, energy consumption appears to increase more or less linearly with ethanol production, crop prices (per bushel) increase at a somewhat more than linear rate. Doubling the amount of ethanol produced more than doubles the size of the increase in wheat prices. (For purposes of comparability, all price increases shown in the exhibit are stated as a percentage of the base-case price.[1]) These results, like all those produced by the model, do not reflect the effect of increased prices on demand, an effect which would undoubtedly temper the size of any price rise.

Additional information about the earlier ISU analyses can be obtained in Turhollow (1982) and Turhollow, Christensen and Heady (forthcoming).

A.3 Energy Credits for Ethanol By-Products

Both the dry and wet milling alcohol processes produce animal feed by-products and the wet milling process produces oil from corn or grain sorghum. These oils compete with other vegetable oils, including soy oil, while the other products displace both soy meal and corn as a source of protein and energy. The typical crude protein content of the various feed products (Feedstuffs, 1981) are:

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[1] *It may be observed that Scenario 6H3 results in percentage price increases which are somewhat smaller than those of Scenario 6L3. These percentages, however, are relative to base-case prices which are substantially higher under the high-export scenario of 6H3 than under the low-export scenario of 6L3.*

Corn	9%	Distillers Dark Grains (DDG)	27%
Soybeans	38%	Gluten Feed	21%
Soy Meal	44%	Gluten Meal	60%

Energy savings result from both reduced agricultural production of soybeans and feed grains, and from reduced crushing of soybeans (and other crops) to produce vegetable oil. The estimate of the effect on agricultural energy consumption of using corn and grain sorghum for ethanol production developed by the ISU Model incorporates the effect of all changes in agricultural production, including reduced production of soybeans. This energy credit is quite substantial. Data produced by the ISU Model (see Section A.2.1) suggest that without this credit incremental agricultural energy consumption would be about 25 percent higher.

Reduced energy consumption for the extraction of vegetable oils as a result of the by-product oils from corn and grain sorghum is not reflected in the model's results and must be estimated separately. It is assumed that all oil replaced is soy oil. Soy oil and soy meal are produced by crushing soybeans and extracting the oil, a process performed primarily to obtain the oil. The average energy consumed per pound of soy oil produced is shown in Exhibit A-26. By-product oil production is 0.60 pounds per gallon of ethanol when corn is used as the feedstock and 0.37 pounds per gallon when grain sorghum is used. For the mix of feedstocks indicated by the model, a national average of 0.56 pounds of oil is produced per gallon of ethanol.

The energy used for milling is 3,723 Btu per pound of oil. This is equivalent to 1,167 Btu per pound of soybeans used, and is comparable to the 1,032 Btu per pound value published by the American Soybean Association (Erickson and Dixon, n.d.) and to 1,120 Btu per pound (on a fuel-consumption basis) for a mill studied by Battelle (Devine, 1977).

A.4 Land Availability and the Potential for Obtaining Ethanol from Grain

In considering our nation's ability for obtaining ethanol from grain, questions are frequently raised about the availability of land for increasing grain production. The U.S. Department of Agriculture Soil Conservation Service (SCS) conducted a land inventory survey in 1977. On the basis of this survey, SCS estimated the potential for converting pasture and rangeland, forests, and other land into cropland given commodity price relationships and development and production costs that prevailed in 1976.

EXHIBIT A-26: ENERGY CONSUMPTION FOR PRODUCING SOY OIL

(per pound of oil produced)

	Petroleum Products						
	Motor Gasoline (gal)	Distillate (gal)	Residual Fuel (gal)	Natural Gas (cu ft)	Coal (1) (lb)	Total Petroleum Products (Btu)	Total Energy (Btu)
Net shipments in 1977 (2): 14,846 MM lbs							
Total energy consumption in 1977 (3):							
— Electricity: 1422.8 MM kwhr					0.089		999
— Direct fuels:		0.00301	0.00296	1.50	0.029 (6)	865	2,724 (5)
Distillate: 1062.7 M bbl							
Residual: 1045.4 M bbl							
Natural gas: 22.3 B cu ft							
Coal na (4)							
		0.00301	0.00296	1.50	0.118	865	3,723

*Less than 0.0005 gal/bu.

(1) Assumes use of 11,250 Btu/lb coal.
(2) DOC, 1980b.
(3) DOC, 1980c.
(4) Data for coal use withheld by Census.
(5) Estimated directly from source data.
(6) Estimated by assuming that all energy from sources not separately identified was obtained from coal.

These estimates are presented in Exhibit A-27. Potential cropland was classified four ways, depending on the ease of conversion and environmental restrictions:

- Land rated as having "zero potential" has virtually no cropping potential and consists primarily of land with very poor soil characteristics for crop production.

- Land classified as "low potential" indicates that conversion is unlikely in the foreseeable future because of existing development problems.

- "Medium potential" land includes areas that could be converted in the long-run with adequate care to minimize any environmental degradation. This category includes land that is poorly drained, subject to wind or water erosion, or that could produce only lower-yielding crops.

- Land with "high potential" for conversion is described as having low or no conversion costs and situated in a locality where similar land had undergone conversion in prior years. These lands would be expected to convert to cropland over the next 10-15 years if economic conditions were to continue about as they were in 1976.

It can be seen from Exhibit A-27 that 36.2 million acres have been identified as having high potential for conversion to cropland, and another 90.8 million acres as having medium potential.

As previously observed, the ISU Model indicates that, under 1981 conditions, the use of grain to produce six billion gallons of ethanol would result in increasing land used for crops by only 8.3 million acres (see Exhibit A-20, above). This estimate of increased land use reflects the effect of reduced production of soybeans (a relatively land-intensive crop) as well as that of increasing yields through greater fertilization and irrigation. The model incorporates the SCS data on land availability and uses these data in analyses of future production in estimating the extent to which grain production would be increased by use of more cropland and the extent to which it would be increased through other means. The results of the model runs performed for this study indicate that, under 1981 conditions (i.e., no increase in available land), there is sufficient land available to produce six billion gallons of ethanol from grain; though, as shown in Exhibit A-23, some increase in crop prices is likely to result.

EXHIBIT A-27: POTENTIAL FOR CROPLAND OF 1977 PASTURE FOREST, AND OTHER LAND, BY STATE

State	High Potential	Medium Potential	Conversion Unlikely	Zero Potential	Total
	- - - - - -	- - - - - -	1000 Acres	- - - - - -	- - - - - -
Alabama	1,064	3,083	7,428	12,923	24,498
Arizona	155	216	3,625	34,327	38,323
Arkansas	657	2,634	8,243	7,868	20,402
California	800	2,009	5,029	30,591	38,429
Colorado	365	2,369	7,570	19,856	30,160
Connecticut	23	89	306	1,420	1,838
Delaware	28	87	186	194	495
Florida	1,117	2,534	11,022	8,754	23,427
Georgia	2,120	3,670	8,484	11,502	25,776
Hawaii	39	62	543	2,674	3,318
Idaho	525	916	1,727	9,318	12,486
Illinois	582	1,385	2,414	3,228	7,609
Indiana	804	1,008	2,068	2,909	6,789
Iowa	700	1,488	2,144	2,771	7,103
Kansas	1,893	3,673	5,593	9,622	20,781
Kentucky	1,302	1,801	2,936	11,011	17,050
Louisiana	1,129	1,864	6,272	10,683	19,948
Maine	29	286	9,093	8,621	18,029
Maryland	145	382	1,116	1,466	3,109
Massachusetts	33	144	764	2,353	3,294
Michigan	561	1,409	5,750	11,790	19,510
Minnesota	1,108	2,845	8,516	9,219	21,688
Mississippi	1,306	2,491	4,934	10,319	19,050
Missouri	2,226	4,395	7,154	10,881	24,656
Montana	1,339	4,360	11,264	32,306	49,269
Nebraska	1,083	2,871	7,260	14,916	26,130
Nevada	50	238	1,669	7,212	9,169
New Hampshire	27	217	1,998	2,080	4,320
New Jersey	116	310	701	1,482	2,609
New Mexico	474	822	8,638	37,985	47,919
New York	358	1,352	4,569	14,258	20,537
North Carolina	1,398	3,661	5,932	9,001	19,992
North Dakota	984	1,898	4,581	6,568	14,031
Ohio	528	1,394	3,490	4,360	9,772
Oklahoma	1,683	4,119	7,564	15,483	28,849
Oregon	325	862	3,042	18,549	22,778
Pennsylvania	270	1,160	4,328	12,536	18,294
Rhode Island	5	18	54	294	371
South Carolina	629	1,635	6,126	4,307	12,697
South Dakota	1,090	4,403	7,602	13,328	26,423
Tennessee	1,428	2,351	3,626	10,428	17,833
Texas	3,534	10,727	46,960	65,280	126,501
Utah	73	447	1,166	12,347	14,033
Vermont	45	168	931	3,470	4,614
Virginia	546	1,605	5,732	9,489	17,732
Washington	506	1,049	3,247	15,669	20,471
West Virginia	64	388	1,302	10,493	12,247
Wisconsin	618	2,041	7,582	8,583	18,824
Wyoming	253	1,688	5,064	22,038	29,043
Caribbean	78	150	77	1,140	1,445
Total	36,215	90,774	268,422	587,902	983,313

Source: USDA, 1979a.

Indeed, since agricultural production can be expanded through various combinations of increasing cropland used, irrigating more land, and applying more fertilizer, land availability itself does not present an absolute limit on the amount of grain used for ethanol production. However, increasing the amount of grain used for this purpose will affect crop prices to an increasing degree. Under 1981 conditions, the ISU Model indicates that producing six billion gallons of ethanol from grain will result in about a four percent increase in the price of wheat and an eight percent increase in the price of feed grains. The results of the earlier ISU analyses (discussed in Section A.2.2, above) suggest that, if other demands for agricultural products are not reduced, doubling the amount of grain used for ethanol will more than double the size of these price increases. Thus, the limit on our ability to obtain ethanol from grain is due not to limits on land availability, but to whatever limits may exist on our willingness to pay higher prices for agricultural products, or to reduce exports or domestic consumption of these products.

APPENDIX B

ETHANOL FROM GRAIN

Processes for the conversion of grain to ethanol are generally divided into those that use dry milling and those that use wet milling. In this appendix, both dry milling and wet milling technologies are considered. There are many variations possible upon these two major approaches, and the sensitivity to some of these variations is explored. Nevertheless, consideration of every ethanol technology currently being offered is beyond the scope of the study.

In general, the wet milling processes consume slightly less energy per gallon ethanol than dry milling processes. The wet milling processes also require higher investment and produce more co-products along with the ethanol.

B.1 Dry Milling

Dry milling technology is relatively straightforward. As the name implies, the milling or size reduction of the grain is done in the absence of water. The entire kernel of grain is reduced in size, usually to pass through a 20 mesh screen without any attempt to separate the various components of the grain. In wet milling the grain is separated into the starch, gluten, and germ during the milling operation.

B.1.1 Process Selection

There are several vendors of proprietary dry-milling ethanol technology. These include ACR, Buckau-Wolf, Katzen Associates, Vulcan-Cincinnati, and Vogelbusch. In addition, a number of engineering firms will design dry milling alcohol plants using various combinations of proprietary and nonproprietary technology. While there are a number of differences between the technologies offered by various vendors, the energy consumption is most affected by the choice of the distillation system, by the use of cogeneration, by the choice of the evaporation system, and by the quantity of water which must be evaporated (which may be influenced by the use of recycle in the process).

The design chosen for analysis in this study is very similar to the design used in the U.S. Department of Energy (DOE) report, Grain Motor Fuel Alcohol Technical and Economic Study (Katzen, 1979). This design was selected because it is in the public domain and because it is one of the more energy efficient designs available. Those portions of the published design which were not considered to be commercially proven state-of-the-art were replaced with proven technologies. The technologies changed were the drying system for the distillers dark grains (DDG) and the flue-gas desulfurization system used in conjunction with the coal-fired boiler.

The design selected for analysis includes vapor recompression evaporators, use of high pressure steam in extraction turbines to provide shaft power to the evaporator compressors, and a cascaded azeotropic distillation system for ethanol purification. The distillation system is similar to a double effect evaporator in energy consumption. Overall, the design selected consists of proven technologies and is considered to be very energy efficient.

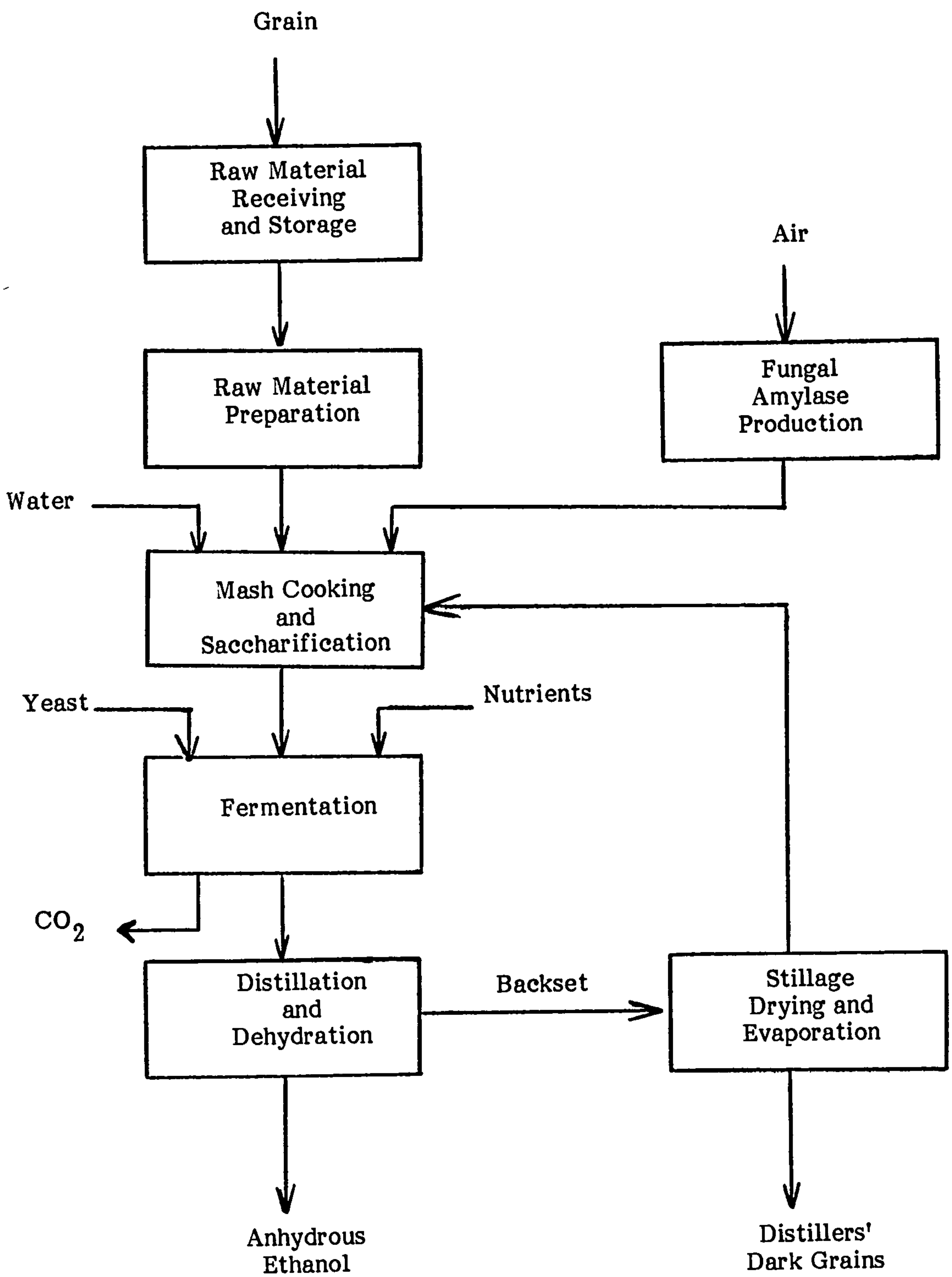
B.1.2. Process Description

Exhibit B-1 is a simplified block flow diagram of the process steps in the manufacture of ethanol from corn based on a typical, currently available dry-milling technology. The grain is received in bulk by rail or truck and is stored in a grain elevator or in storage bins. From there it is transferred periodically to a surge hopper, which feeds the process plant as required.

Grain from the surge hopper is first cleaned to remove sand, tramp metal, and light dusty (cob & chaff) materials. It is then ground to the required size in a hammer mill. The ground grain is conveyed to a precooker where it is mixed with water and recycled stillage at about 150° F. The grain slurry is then cooked for about 1.5 minutes at 350° F in a continuous cooker.

The cooked mash is cooled to about 145° F in a series of flash coolers which operate at progressively lower temperatures. After cooling, an enzyme (fungal amylase) is added to convert the starch to sugar. This enzymatic hydrolysis step is also known as saccharification.

EXHIBIT B-1: SIMPLIFIED FLOWCHART OF DRY-MILLING PROCESS FOR OBTAINING ETHANOL FROM GRAIN



In the design considered for this analysis, the fungal amylase is produced in the ethanol facility. This is economic only for large-scale plants; in most small-scale ethanol plants, the enzyme would be purchased. Manufacturers of commercial enzymes contacted during this study were unable to provide data on the energy consumed in enzyme manufacture except to indicate that the energy cost was small compared to other costs. By including enzyme manufacture in the ethanol plant, an attempt was made to account for the energy invested in enzymes. As can be seen in the data presented in Subsection B.1.4, the energy consumed in enzyme manufacture is indeed small, though the energy required to produce commercial enzymes may be slightly different.

Following saccharification, the mash is cooled to about 80° F. Chemical nutrients and yeast are added and the mixture is allowed to ferment in batch fermenters. Continuous fermentation has been proposed and has been demonstrated on pilot-plant scale, and in some commercial operations. Changing from batch to continuous operation might improve the economics but would have little effect on the energy requirements. During fermentation, the mixture is kept between 77° and 90° F. Carbon dioxide released by the fermentation process is exhausted to the atmosphere through a condenser, which removes entrained liquid and returns it to the fermenter.

Upon completion of fermentation, the alcohol is recovered and purified in a series of distillation columns. The bottom stream from the first column, which is known as the stripping column, contains water and suspended and dissolved organic materials. The solids are removed by centrifugation. The remaining liquid is then concentrated by evaporation, recombined with solids, dried (to 10% moisture content), and sold as distillers' dark grains (DDG). The evaporation and drying of DDG is one of the major energy consumers. Nevertheless, the recovery of this by-product is essential to the overall economics of ethanol manufacture from grain. DDG contains most of the protein originally present in the grain and can be marketed as animal feed.

The evaporation system selected for this analysis is a vapor recompression evaporator with the compressor driven by a steam turbine. The exhaust low-pressure steam from the turbine is used to provide process heat during distillation, mash-cooking and grain-drying operations. This cogeneration of shaft power and process heat improves the energy efficiency of the overall process but requires additional capital investment. Other typical designs use multiple-effect evaporators, which also reduce steam

consumption. The choice of the evaporation system in a plant depends on a detailed economic comparison. Such a comparison, however, is beyond the scope of this study.

The concentrated stillage from the evaporator (55% solids content) is finally dried in a steam tube dryer using steam from the boiler. This makes it possible to use coal as the only process fuel. Gas-fired dryers, which directly contact hot combustion gases with the wet distillers' grains, are used in many designs. One published design (Katzen, 1978) uses combustion gases from a coal-fired boiler for drying the stillage. Since the DDG will be used as animal feed, there is the possibility that the components of fly ash from coal combustion may contaminate the DDG. In such cases, indirect contact dryers would suffice; however, there would be a small energy penalty.

The overhead from the stripping column contains a mixture of water, ethanol, and impurities. These include both low-boiling impurities (esters and aldehydes) and high-boiling impurities (fusel oil). This mixture is purified in a rectifying column. The esters and aldehydes would be recovered and recycled to the boiler for use as fuel within the plant. The quantity of esters and aldehydes produced will depend on the operation of the fermenters; it is generally small. In many designs, the stripping and rectifying columns are combined into a single column as in the pressure stripper-rectifier of the Katzen design.

The fermented beer is stripped (of stillage) and concentrated to about 95 percent (by volume) alcohol in the same column. From here, it is sent to a dehydration column where the alcohol is further concentrated to anhydrous (99.5 percent) ethanol by azeotropic distillation. In azeotropic distillation, a dehydrating agent (such as benzene, ethyl ether, or other hydrocarbon) is added to remove the water. Fusel oil, which is removed from an intermediate plate of the rectification section and separated by decantation, is combined with the product alcohol. This fusel oil contributes slightly to the energy content of the liquid fuel. There are small dehydrant losses during the azeotropic distillation. This small dehydrant loss was not included in the net energy balance because it is believed that most of the loss ends up with the liquid fuel product.

The distillation columns are cascaded so that the overhead condenser from the rectifying section is the reboiler for the dehydration column. This concept, which is similar to double effect evaporation, has been used in the petroleum refining and petrochemical industries for years. It is fairly new to ethanol production, however.

Among others, Katzen and Vulcan-Cincinnati use this concept in their proprietary ethanol purification designs. This concept offers significant energy savings over the conventional ethanol purification. Both Katzen and Vulcan-Cincinnati distillation systems require about 21.5 pounds steam per gallon of anhydrous ethanol.

Process steam at 600 psig and 600° F is generated in a pulverized coal-fired boiler equipped with cyclones and a double alkali flue-gas desulfurization system. The cleaned flue gas is reheated by 50° F with steam before discharge to the stack. The overall boiler efficiency was assumed at 86 percent, which is typical of pulverized coal boilers with rated capacities above 200,000 pounds per hour (McKee, 1979). This would be suitable only for large ethanol plants. The impact of plant size is discussed under the section on sensitivity analysis.

B.1.3 Process Chemistry

The chemistry of grain fermentation is complex, but the basic concepts and overall reactions are simple. The major reactions reduce starch to sugar, which is then fermented to ethanol.

Starch is first gelatinized by cooking. The starch is then hydrolyzed to sugars by enzymes.

$$(C_6H_{10}O_5)_n + nH_2O \rightarrow n\,C_6H_{12}O_6$$

The hydrolysis or saccharification usually occurs in two steps. First the molecular weight of starch is reduced by cleavage catalyzed by alpha-amylase, followed by conversion of the resulting malto-dextrins to glucose by the enzyme amyloglucosidase.

The sugar is then converted to ethanol and carbon dioxide by yeast in the fermentation step. The overall reation is

$$C_6H_{12}O_6 \rightarrow 2\,C_2H_5OH + 2\,CO_2$$

There are many intermediate reactions. There are also some side reactions in which various impurities, especially higher alcohols, are formed. The impurities are made from amino acids, sugars and other carbohydrates.

B.1.4 Energy and Materials Consumption

The material and energy consumption for the dry-milling ethanol process using corn as a feedstock are:

Corn	0.388	bushels/gal ethanol
Coal	0.0022	ton/gal or 0.566 Btu/Btu
Electricity	1.31	kwhr/gal or 0.162 Btu/Btu
Makeup Azeotroping Agent	0.00018	gal/gal
Lime	0.00012	ton/gal

Material and energy consumption for this process when grain sorghum is used as a feedstock was not analyzed separately, but are similar.

The coal used was assumed to be an Illinois No. 6 with 12 percent moisture and a higher heating value as received (wet) of 10,630 Btu/lb (12,080 Btu/lb dry basis). The sulfur content was 3.8 percent on a moisture free basis. Estimated energy consumption for producing lime is shown in Exhibit B-2.

In addition, about 0.02 (formerly 0.05) gallons gasoline are consumed per gallon ethanol as a denaturant (27 CFR 212.13, FR 8417, Jan 81). This gasoline is not included in the overall energy balance because it is neither added nor removed from the fuel available for transportation. It is merely diverted temporarily from the gasoline pool to make the fuel grade ethanol unfit to drink.

Similarly, the makeup azeotroping agent (benzene or other hydrocarbon) may be ignored in the energy balance because the losses will end up in the fuel. Furthermore, the total energy content of the azeotroping agent is small as can be seen from the data above.

The energy in the various steps of the dry milling process is summarized in Exhibit B-3. Most of the energy is consumed as process steam generated by burning coal. The most energy intensive steps are the distillation of ethanol and the concentration and drying of DDG (distillers' dark grains).

The output from the process is fuel grade ethanol and DDG. Small amounts of higher alcohols (fuel oils) produced in the fermentation are blended with the ethanol and

EXHIBIT B-2: ENERGY REQUIRED FOR PRODUCTION OF LIME

Assumptions	Petroleum Products: Motor Gasoline (gal/ton)	Petroleum Products: Distillate (gal/ton)	Petroleum Products: Residual Fuel (gal/ton)	Natural Gas (M cu ft/ton)	Coal and Other (tons coal/ton)	Total Petroleum Products (M Btu/ton)	Total Energy (M Btu/ton)
Total production in 1977: 1419 M tons (1)							
Total energy consumption in 1977 (2):							
— Electricity: 830.5 MM Kwhr					0.271		6,100
— Direct fuels:		9.13	35.6	15.8	1.972 (4)	6,600	67,100 (3)
Distillate: 308.6 M bbl							
Residual: 1202.7 M bbl							
Natural Gas: 22.5 B cf							
Coal: 2033.4 M tons							
TOTAL ENERGY CONSUMED		9.13	35.6	15.8	2.243	6,600	73,200 (5)

Sources:

(1) Estimated from DOC, 1980a.

(2) DOC, 1980c.

(3) Estimated directly from source data. Includes coke, other purchased fuels, and undistributed fuels.

(4) Equals number of 22.5 MM Btu/ton coal necessary to produce all energy not accounted for by petroleum and natural gas consumption. Actual consumption of coal is 1.433 ton per ton of lime produced.

(5) Does not include energy for mining limestone (about 300,000 Btu per ton of lime produced) or for transporting limestone (about 1 to 2 million Btu per ton of lime, depending on transport mode and distance).

EXHIBIT B-3: ETHANOL FROM CORN: ENERGY BALANCE FOR DRY MILLING PROCESS

Process Section	Electricity[c] Btu per Btu Ethanol	Coal Btu per Btu Ethanol	By Product[b] Consumed Btu per Btu Ethanol	By Product[b] Produced Btu per Btu Ethanol	Hp Steam[a] Consumed Btu per Btu Ethanol	Hp Steam[a] Produced Btu per Btu Ethanol	Mp Steam[a] Consumed Btu per Btu Ethanol	Mp Steam[a] Produced Btu per Btu Ethanol	Lp Steam[a] Consumed Btu per Btu Ethanol	Lp Steam[a] Produced Btu per Btu Ethanol
Corn Receiving Storage & Milling	-0.010									
Mash Cooking & Saccharification	-0.004						0.136			0.039
Enzyme Production	-0.033						0.003			
Fermentation	-0.006									
Distillation	-0.003						0.262		0.039	
DDG Recovery	-0.044				0.479		0.158	0.444		
Storage & Denaturing	-0.001									
Steam Generation	-0.003	-0.566	0.009			0.479		0.139		
FGD Reheat							0.009			
Utilities & Misc.	-0.058			0.009			0.015			
TOTAL	-0.162	-0.566	0		0		0		0	

(a) Hp steam is at 600 psig, 600 F; Mp steam at 150 psig, saturated; Lp steam at 15 psig. Energy of steam taken as enthalpy above water at OC (32F).
(b) By-product represents sludge from water treatment plus a small amount of ester aldehyde from distillation.
(c) Electricity at fuel needed to generate (10,400 Btu/Kwh).

included in the ethanol volume. When corn is used as a feedstock, the DDG by-product amounts to about 7 lb per gallon ethanol (Katzen, 1979). When grain sorghum is used as a feedstock, approximately the same amount of DDG is produced, though it has a slightly lower energy value and a slightly higher protein value (Jurgens, 1978); in the analysis performed by the ISU Model, the grain-sorghum/DDG was taken to be equivalent to 6.9 lb per gallon of ethanol on a feed-value basis.

Sludge from water treatment and a small amount of light ends from the distillation are burned as boiler fuel, thereby reducing the coal consumption slightly.

The moist sludge from flue gas desulfurization is about 0.85 lb per gallon ethanol. It has been assumed that this sludge would be landfilled adjacent to the plant with negligible energy penalty for loading, transporting, and dumping.

B.2 Wet Milling

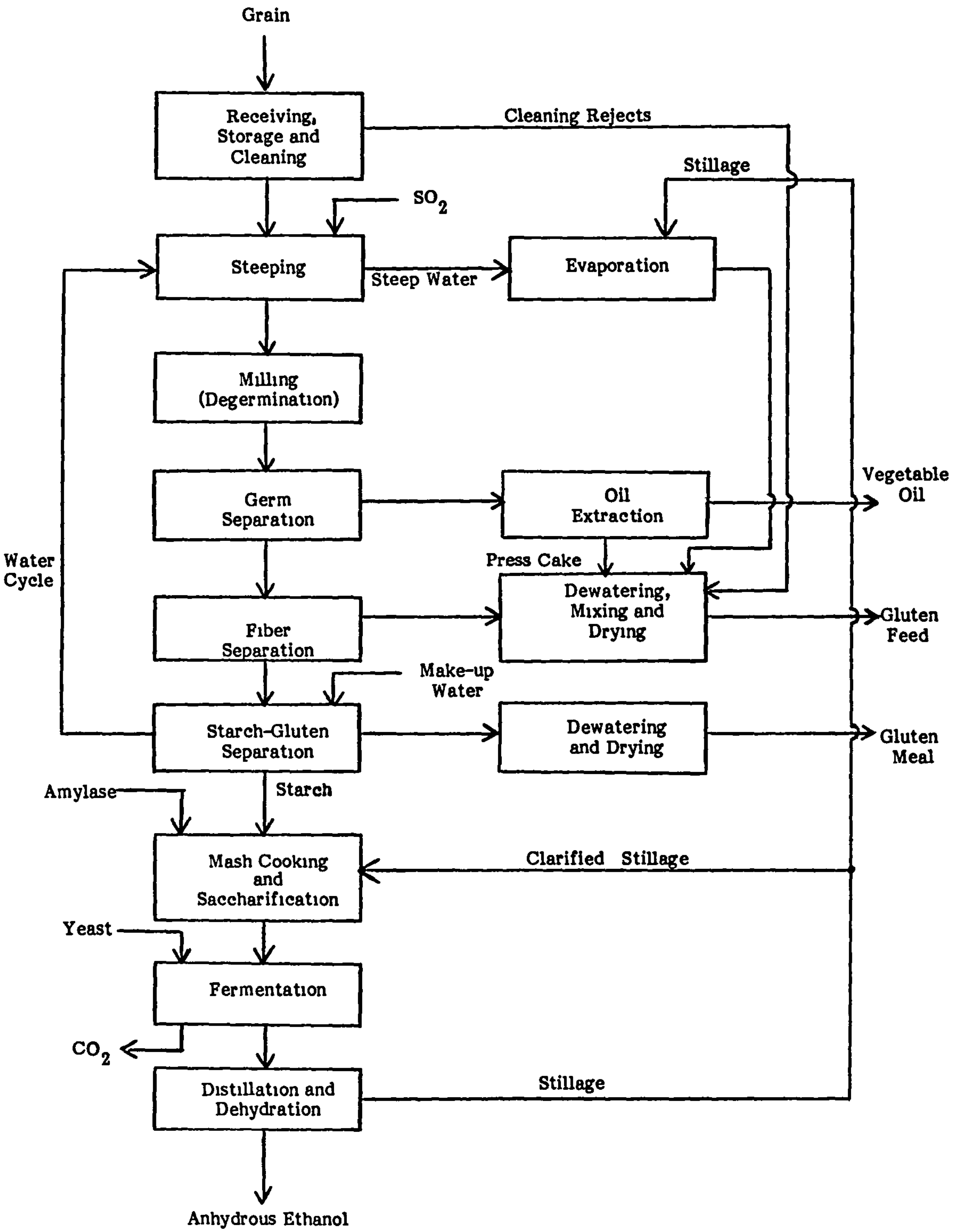
The following is an analysis of the energy balance for the production of ethanol from corn by a wet-milling process. The selected process scheme includes the production of by-product corn oil, gluten feed, and gluten meal.

It should be noted that each wet miller incorporates proprietary variations in the process. The information given here is considered typical of current commercial practice. From an energy use viewpoint, the water balance is a key item. If more water can be recycled and reused within the process, less must be evaporated, and, therefore, less energy will be consumed.

B.2.1 Process Description

The wet milling of grain is more complex than dry milling. In addition to saccharification, fermentation, and alcohol recovery operations, the wet-milling process requires several major steps. These include steeping, milling, germ separation, oil extraction, fiber separation, starch-gluten separation, and dewatering, mixing and drying. A simplified overall process flow diagram is shown in Exhibit B-4 and described in brief below.

EXHIBIT B-4: SIMPLIFIED FLOWCHART OF WET-MILLING PROCESS FOR OBTAINING ETHANOL FROM GRAIN



Shelled corn is received in bulk by either truck or rail. It is stored and cleaned to remove all large and small pieces of cob, chaff, sand, and other undesirable foreign material. This section would use electric power to operate conveyors, screens, and aspirators.

The cleaned corn is then steeped for about 30-50 hours at a temperature of about 125^{o} F. Wash water from the starch separation is sent countercurrently to the steeping operation via fiber separation and degermination. An SO_2 concentration of about 0.1-0.2 percent is maintained in the wash water before it enters the steeping operation.

After steeping, the corn is degerminated in an attrition (cracking) mill. The mill gap is adjusted to maximize recovery of germ and to minimize breakage. The germ is first separated from starch, gluten, and fiber in a hydrocyclone and then washed and dewatered by pressing prior to oil extraction. The electrical power used for the dewatering machinery and the steam requirements of the dryer are the major energy consumers in this section.

Corn oil may be extracted from the germ by either mechanical or solvent processes. For this study, the extraction of oil by a mechanical process is assumed. The energy consumed in a mechanical process is mostly electric power, with very little steam use. The press cake from the corn oil extraction process is blended into the corn gluten feed. A significant portion of corn oil in the germ is lost through the press cake. The corn oil recovery can be increased by adding a solvent extraction step. Solvent extraction increases capital requirements and energy consumption. The additional energy requirements are mostly steam plus solvent losses. Recovery of additional corn oil by solvent extraction is usually economic only for very large corn oil plants.

The fiber is separated from the starch and gluten by screening. The fiber is then washed and dewatered by means of screens and presses, respectively. Recycled water is used to wash the fiber, thereby minimizing water consumption and overall evaporaton requirements. The wet fiber is mixed with corn cleanings, the bottoms from the exhaust steep-liquor/stillage evaporator, and press cake, and then dried to form the gluten-feed product. Here also, the dewatering and drying operations are the major energy consumers.

Starch and gluten are separated in a centrifuge. The separated gluten is dewatered by filtration and then dried to form the product known as gluten meal. The majority of the energy consumption occurs in the centrifuging and drying operations. After deglutenization, the starch is washed and subjected to cooking and saccharification. These operations are similar to those for the dry-milling alcohol process. Flash steam from cooking is used to heat the boiler feed water.

The saccharified solution is then sent to the fermentation section. Fermentation is conducted in a batch mode and may be followed by centrifuging to recover yeast. The fermentation beer is finally sent to distillation, which is similar to the dry-milling case.

Exhausted steep liquor and clarified stillage from the stripper column are concentrated in an evaporator. The concentrated slurry (about 45 percent solids) from the evaporator is then mixed with press cake, wet fiber and corn cleanings to form the gluten feed. The evaporator was assumed to be a vapor recompression type with the compressor driven by a steam turbine.

Steam used in the process is mostly at 150 psig. Steam is generated at 600 psig, and 600° F in a pulverized coal-fired boiler with a boiler efficiency of 86 percent. The high pressure steam is then reduced to process steam pressure through the compressor turbine which drives an electric generator. Part of the plant's electric power is provided by this cogeneration. The boiler is equipped with a double alkali flue-gas desulfurization system.

The major reason why wet milling requires less steam energy than dry milling is because of the reuse of water. In the wet-milling process, a portion of the stillage is centrifuged, and the clarified water is recycled to the cooking step. Water from the deglutenizing and starch washing steps is recycled to washing operations associated with the fiber and germ separation operations, and to steeping. The counter-current water flow and water reuse minimizes the evaporation load.

Another major difference between the two process is that in wet milling nearly all of the nonfermentable components of grain are removed prior to the cooking and saccharification.

B.2.2 Energy and Materials Consumption

The material and energy consumption for the wet-milling ethanol process using corn as a feedstock are:

Corn	0.388 bu/gal ethanol
Coal	0.00219 ton/gal or 0.553 Btu/Btu
Electricity	1.26 kwhr/gal or 0.156 Btu/Btu
Makeup Azeotroping Agent	0.00018 gal/gal
Lime	0.00012 ton/gal
Sulfur Dioxide	0.0445 lbs/gal

Material and energy consumption for this process when grain sorghum is used as a feedstock was not analyzed separately, but is likely to be similar.

As in the dry milling case, the coal used was assumed to be an Illinois No. 6 with 12 percent moisture and a higher heating value as received (wet) of 10,630 Btu/lb (12,080 Btu/lb dry basis). The sulfur content was 3.8 percent on a moisture-free basis. As in the dry milling process, the makeup azeotroping agent and the 0.02 gallon gasoline denaturant per gallon ethanol may be excluded from the overall energy balance.

The energy consumed in various steps of the wet milling process is indicated in Exhibit B-5. Most of the process energy is provided by burning coal to raise steam. In addition to the electricity generated within the process, a significant quantity of electricity must be purchased.

The output from the wet-milling process are fuel grade ethanol (99.5%), vegetable oil, and various animal feed products. When corn is used as the feedstock, the by-products are:

Corn Oil	0.60 lb/gal ethanol
Gluten Meal	1.08 lb/gal
Gluten Feed	5.5 lb/gal

When grain sorghum is used, the same total amount of gluten meal and gluten feed are produced, but a larger portion of the by-product is gluten meal (which has a higher

EXHIBIT B-5: ETHANOL FROM CORN: ENERGY BALANCE FOR WET MILLING PROCESS

Process Section	Electricity[a] Consumption Btu per Btu Ethanol	Electricity[a] Generation Btu per Btu Ethanol	Coal Consumed Btu per Btu Ethanol	Hp Steam[b] Consumed Btu per Btu Ethanol	Hp Steam[b] Produced Btu per Btu Ethanol	Lp Steam[b] Consumed Btu per Btu Ethanol	Lp Steam[b] Produced Btu per Btu Ethanol
Receiving, Storage and Cleanings	0.005						
Steeping	0.007					0.009	
Degermination, Germ Dewatering and Drying	0.018					0.028	
Fiber Separation, Dewatering, Mixing and Drying	0.046					0.091	
Enzyme Manufacture	0.033					0.003	
Gluten Separation and Drying	0.017					0.025	
Starch Washing, Cooking and Saccharification	0.008					0.053	
Fermentation	0.006						
Distillation and Dehydration	0.003					0.304	
Steep Liquor and Stillage Evaporation	0.006			0.179		0.008	0.166
Corn Oil Extraction	0.008						
Electricity Generation		0.075		0.408			0.378
Steam Generation and Utilities	0.065		0.553		0.587		
Flue Gas Reheat						0.010	
Miscellaneous	0.009					0.013	
Total	0.156		0.553	0		0	

(a) Electricity taken as fuel to generate, i.e., 10,400 Btu/kwh.
(b) Hp steam is at 600 psig, 600 F; Lp steam is at 150 psig, saturated.
Energy steam taken as enthalpy above water at 0 C (32 F).

protein content); these differences are reflected in the data used by the ISU Model. Oil production from grain sorghum, however, is only 0.37 lb/gal of ethanol.

As in the dry milling case, there is also about 0.85 lb/gal moist solids from the flue gas desulfurization which would be disposed of at an adjacent landfill.

B.3 Discussion and Sensitivity Analysis

Process energy consumed is nearly the same for both processes analyzed in this study:

	Dry milling	Wet milling
Coal	0.57	0.55
Electricity Fuel	0.16	0.16
	0.73 Btu/Btu of ethanol	0.71 Btu/Btu of ethanol

These figures do not include the energy embodied in the feedstock or in the by-products.

A conventional (and nonrenewable) fuel, coal, has been assumed as the boiler fuel. There is now some interest in the use of methane derived from renewable sources as the boiler fuel for small- and medium-scale plants. Two possible methane feedstocks being considered are still bottoms or, if a feedlot is nearby, manure (Alcohol Week, July 26, 1982). The use of methane derived from either of these feedstocks would effectively eliminate nonrenewable fuel consumption directly associated with the boiler operation (except for a small amount of fuel required for manure transport). However, this savings would be partly offset by increased agricultural consumption of nonrenewable fuels, since manure would otherwise be used as fertilizer while still bottoms would otherwise be dried to produce feed by-products; diversion of either of these substances to fuel use would result in increased energy consumption for production of feed or fertilizer. Although an overall reduction in the consumption of nonrenewable fuels would be likely, some increase would occur in the consumption of natural gas and, if still bottoms are used, in the consumption of petroleum products.

Another alternative boiler fuel would be agricultural residues. Energy requirements for collecting, drying and transporting agricultural residues are discussed in Appendix E.

Use of agricultural residues instead of coal would result in an overall reduction in the consumption of nonrenewable fuels but in some increase in the consumption of petroleum products and natural gas.

The energy consumption figures shown above are lower than the published value for one commercial process of 72,500 Btu/gallon or 0.86 Btu/Btu (Bohler Brothers of America, 1981) and higher than the published value of 0.65 Btu/Btu for a much quoted conceptual design (Katzen, 1979). Both of these are dry milling processes. The latter design incorporates energy conservation features which this study does not consider commercial state of the art. That design differs from the one used in this study primarily in the method of drying DDG and of desulfurizing flue gas.

The largest consumers of process energy are the distillation and dehydration of the ethanol to reduce water concentration to 0.5 percent maximum and the recovery and drying of the animal feed byproducts: DDG for dry milling, gluten feed and gluten meal for wet milling.

The energy required for distillation is sensitive to the selection of the distillation process and to the use of heat recovery whenever feasible. The designs selected for this study use one of the most energy-efficient distillation systems currently available. This energy efficiency is achieved by cascading the distillation column so that the condenser of one still becomes the reboiler for another. By this technique the steam energy for distillation is reduced to about 0.30 Btu/Btu ethanol compared to 0.37 - 0.46 Btu/Btu for conventional distillation (Black, 1980). Extractive distillation with gasoline is also an energy efficient commercially available separation technique which consumes about 0.35 Btu/Btu, but extractive distillation with ethylene glycol consumes about 0.69 Btu/Btu (Black, 1980). Other separation methods which are not yet commercially available are discussed elsewhere in this report.

Since process heat is consumed as steam but derived from coal (or other fuel), the boiler efficiency can have a significant impact on the overall energy balance. For this study, a pulverized coal-fired boiler with an overall efficiency[1] of 86 percent was

[1] *Overall boiler efficiency is defined as energy transferred to the steam divided by the higher heating value of the fuel.*

selected. The pulverized coal boilers are economic only in larger sizes (about 200,000 pounds steam per hour or more) and are suitable for alcohol plants with capacities in excess of 35 to 40 million gallons per year. Smaller plants would use either coal-fired stoker boilers or oil or gas-fired boilers. The typical boiler efficiencies (McKee, 1979) are:

Stoker coal less than 50,000 lb/hr	80%
Stoker coal 100,000 lb/hr steam	84%
Pulverized coal 200,000+ lb/hr	86%
Oil 10,000 - 400,000 lb/hr	85%
Gas 10,000 - 50,000 lb/hr	81%
Gas 100,000+ lb/hr	82%

These efficiencies were based on boiler manufacturer estimates for commercial units. It may be possible to improve the efficiency of some units through careful design and operating control, although this may not be economic at the smaller sizes. One of the reasons for the lower efficiency of stoker boilers is the large amount of excess air required for operation. Because of the boiler limitations, a small alcohol plant with a coal-fired stoker boiler and an otherwise identical design would be expected to consume 1.075 times as much coal per gallon of ethanol as a large alcohol plant.

Plant scale also has an impact on the amount of energy saving equipment which can economically be incorporated into the design. For example, the economic attractiveness of cogeneration decreases as plant size decreases. The analysis of the breakeven size for cogeneration is beyond the scope of this study. In general, as alcohol plant size decreases, unit energy consumption will increase.

For the recovery of the by-products such as gluten meal, gluten feed and germ, steam-tube dryers were considered for the energy analysis. However, in some locations the use of direct or indirect fired natural gas dryers might be more economical than the steam-tube dryers, but the impact on the overall energy balance for the ethanol production would be very insignificant. The direct-fired natural gas dryers appear to be a little more efficient than the steam-tube dryers by about 3 to 4 percentage points.

The energy embodied in the manufacture of lime for the flue gas desulfurization system is significant. The base case assumes coal with 3.34 percent sulfur, and a double alkali

desulfurization system removing 90 percent of the sulfur dioxide and utilizing 5 percent stoichiometric excess of lime. This system consumes 0.00012 ton lime per gallon ethanol, which has an embodied energy of 73.2 million Btu per ton. This is equivalent to 8800 Btu per gallon ethanol.

Using the double alkali desulfurization system, which was chosen for reliability and ease of operation, this embodied energy is directly proportional to the sulfur content of the coal and inversely proportional to the coal heating value. The sulfur content of coal varies over a wide range and is more likely to affect overall energy.

The energy embodied in lime is also sensitive to the fuel and the local environmental regulations. If natural gas were used there would be no need for flue gas desulfurization. Similarly, if the plant were located in an area with less restrictive regulations, a lower fraction of the sulfur would be removed, with a corresponding lower lime consumption.

The energy embodied in lime use is also dependent on the flue-gas desulfurization system selected. If a lime scrubbing system were selected, the stoichiometric excess would be about 25 percent, and the embodied energy in lime would be about 19 percent higher. On the other hand, if limestone were used instead of lime, there would be none of the energy embodied in lime. However, there are few desulfurization units using limestone operating at less than electric utility scale.

Finally, if one used an ammonia scrubbing system as proposed by Katzen (1979) and used the resulting ammonium sulfate solution as fertilizer, there would be no energy penalty. There could be significant economic penalty, however, since a concentrated nitrogen fertilizer, ammonia, would be converted to a dilute nitrogen fertilizer, ammonium sulfate, by the process. A market for the ammonium sulfate would have to be established.

B.4 Potential for Reduced Energy Consumption

Much research attention has been given to ethanol purification, since the distillation of ethanol to meet the 99.5 percent fuel grade specification is a major process energy consumer. The processes under consideration are improved distillation, solvent extraction, and absorption technologies.

The use of vapor recompression in distillation is a commercially available technology that can reduce distillation energy consumption. To be economic, however, one needs a supply of relatively inexpensive shaft power. This is best accomplished by cogeneration. The use of vapor recompression distillation would probably not be economic in a design which already incorporated cogeneration.

Efficient and economic solvent extraction depends upon the choice of the solvent. While the literature abounds with extraction research studies, none has reached commercial status. At present, A.D. Little is developing an ethanol extraction process which uses liquid carbon dioxide as the solvent. Ethanol is recovered by flash distillation of the solvent, followed by recompression and recycle of the carbon dioxide. It has been claimed that this process can recover fuel grade ethanol from fermentation beer with the expenditure of only 8,000 - 10,000 Btu/gal, about one-third that for conventional processes (Eakin, 1981). The economic and continued operability of the process remain to be demonstrated.

Absorption is suitable for removing the last several percent of water from ethanol that has been distilled from fermentation beer. There are two absorption systems that appear promising: molecular sieves and corn meal. Both would replace azeotropic distillation. Molecular sieves are commercially available and may be used by some farm-scale ethanol plants; however no commercial ethanol plant is known to use this technology. The sieves can be used to absorb water preferentially from a water-ethanol mixture. The sieves are usually regenerated with hot gas (about 400° F). The estimated energy required is 4,700 - 6,300 Btu per gallon, or about half the 9,400 Btu of conventional azeotropic distillation (Eakin, 1981).

Cracked corn or corn meal can also be used as an absorbant to remove water from ethanol (Ladisch, 1979). The technology is still being developed, but it appears that the energy consumption to regenerate corn meal when drying from the azeotrope to fuel grade is 600 Btu per gallon (Ladisch, 1980). Furthermore, the regeneration temperature is low (120° C), which enhances the opportunity to use low grade heat. It is possible that the overall process energy can be reduced by stopping the distillation with 10 to 15 percent water remaining and then drying by absorption on corn meal.

Another major energy consumer is the evaporation of stillage to recover DDG in the dry milling process and the evaporation of steep liquor and stillage in the wet milling process. There is a potential to reduce energy consumption by reduction of the quantity of water to be evaporated by higher water recycle. The recycling, however, can have adverse impact on fermentation operations. This is an area for research.

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16 Abstract

In this study, energy requirements for producing alcohol fuels are estimated and are compared to the energy content of the alcohol produced. The comparisons are developed for three alcohol production alternatives: ethanol from grain, methanol from cellulose, and methanol from coal. In the analysis, alcohol fuel and all nonrenewable fuels are valued on the basis of their higher heating value (in Btu), while byproducts and grain and cellulose feedstocks are valued on the basis of the effect their production would have on the consumption of nonrenewable fuels. The effects of changes in agricultural production were analyzed on the basis of their effects on overall agricultural energy consumption (not on average energy consumption associated with present production). All three alcohol production alternatives were found to be effective means of increasing supplies of liquid fuels. The cellulose-to-methanol alternative, however, produces more energy than it consumes. (The favorable energy balance for this feedstock results largely from the use of cellulose as a boiler fuel as well as a feedstock.) The grain-to-ethanol alternative yields a slightly negative energy balance, while the coal-to-methanol alternative (which uses a nonrenewable fuel as both feedstock and boiler fuel) results in a substantially negative energy balance. The report is presented in four volumes. Volume I (NASA CR-168090) contains the main body of the report, and the other three volumes contain appendices:

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